Meteorologic Impacts of Forest Management Activities

on

Wildfire Potential

Part 1 - Technical Report

FINAL REPORT

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Meteorologic Impacts of Forest Management Activities on Wildfire Potential

Part 1 - Technical Report

(Part 2 - Procedures for Extension of Meteorological Observations to Remote Sites is under separate cover)

Prepared by Lee K. Balick

Jack S. Barrows

ABSTRACT

The broad objective of this research is to enable improvements of the assessment of wildfire potential hazard by improving the meteorological inputs to fire hazard models. Two areas for improvement of these data are addressed. First, the climatology of the input variables at sites under consideration is generally not established. The fire climate at these sites must be approximated with data from the most appropriate permanent weather station. Secondly, since fuel management decisions will be based on fire hazard potential, the effects of silvicultural treatments on fire climate is estimated. The research is limited to improved estimates of fire climate at standard instrucment heights above the ground.

The effects of silvicultural treatments are estimated from published observations and the effects are assumed to result from changes of stand density. Changes of maximum and minimum temperature and relative humidity and wind speed are expressed as a function of percent cut and general stand characteristics. Also a method of estimating changes of wind speed with height in clearings is presented.

Decision lead times on the order of two years limit the period of observation to one year or less. Because the remote site is expected to be infrequently attended and only common instrumentation would be available, only the following variables are considered: daily maximum and minimum temperatures, afternoon and morning dew points (which can be converted to relative humidity) and wind speed. Four-year data sets from Idaho and Arizona are used to obtain relationships between remote sites and a nearby "base"

weather station by a stepwise regression technique. Two hundred and sixteen regression equations result from the analysis. Accuracy parameters are examined for each equation. The extent to which the regression equations remain valid from year to year is examined in detail. The accuracy of the estimates on extreme days is also examined.

Procedures and guidelines for the use of the regression technique are given in Part 2 of this report, under separate cover.

Acknowledgements

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Much of the basic data came from related research by the Forest Service. The pioneering work of Mr. Lloyd Hayes at the Priest River Experimental Forest provided essential data for examination of altitude and aspect influences on fuel flammability. Mr. Ralph Campbell, RMF and RES, Flagstaff, Arizona rendered very valuable assistance in assembling fuel and weather data for the Woods Canyon studies on the Coconino National Forest, Dr. R. W. Furman, RMF and RES, assisted in review of the research.

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Meteorologic Impacts of Forest Mangement Activities

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Part 1: Technical Report

1. Introduction and Objectives

1.1 Introduction

Of the three influences of fire behavior, fuel, weather and topography, only fuels can be brought under effective management. One task of fuels management is to determine for a site if fuel treatment is wanted and, if so, what kind of treatment is best. Currently the National Fuel Hazard Appraisal System Research Work Unit is developing methodology for the application of decision analysis techniques to this problem. A crucial phase in these analyses is the establishment of the frequency distribution of wildfire frequency and of fire behavior descriptors. These distributions must be known as a function of time as natural changes of fuel beds occur. They must also be approximated as a function of alternative management activity. With this information the wildfire potential of the site can be established and potential resourse loss can be estimated for each management alternative.

Hirsch (1977) has shown that the distributions of expected fire behavior parameters for a site are influenced more by meteorological variables than any other inputs to his model. Because a "climatology" of fire frequency and behavior of a site is needed for the decision analyses, a good representation of fire climate[1/] is desired. Furthermore, the effects

[1/] The term "fire climate" is defined here as the description over time of the meteorological variables that influence fire behavior and fire hazard. In this report consideration of fire climate is constrained to meteorological variables observed at fire weather stations.

of the management alternatives on fire climate should be estimated. Two main difficulties are encountered here. First, the sites under consideration are generally not instrumented. In mountainous terrain weather and climate change greatly over small distances. The best weather data source is the National Fire Weather Data network but the placement of these stations is notably biased toward valley bottoms and mountain tops. This fact, combined with their relatively low spacial density, prohibit the determination of site specific fire climates desired for decision analysis. The second difficulty is that there is no concise body of knowledge of the effects of silvicultural treatments of fire climate. This research is focused on these two problems.

The effects of treatments on fire climate are considered to result from changes of stand characteristics. (This report is limited to climatological effects as they would be observed by sheltered instrumentation at standard heights above the ground. These are the input data to fire behavior models). The approach to this problem is through a review and synthesis of previous research. Budget and time considerations prohibit the taking of new data and old data is notably scarce. This portion of the research is contained entirely in section 2 of this report.

The second area of research involves the estimation of fire climate at sites which are generally remote from and considerably different than locations with established weather stations. This is a problem that has long plagued resource managers. Research seems to have begun over 50 years ago and no solution has resulted. In fact, research indicates that there may be no one solution within the context of present data and analytical techniques. Physical modeling conceptually has the best promise for a general solution. Models developed to date are very complex, difficult to apply and require input data that are unavailable or difficult to obtain. Nevertheless, they

may eventually provide the best solution. Several observational studies of topographic and vegetative influences on microclimate have been conducted (Hayes, 1941; McHattie, 1966; McHattie, 1970; Hursh, 1948; Wilson, 1970 to name a few) and reviewed (Kitterridge, 1948; Geiger, 1966). The notable characteristic of these studies is that the direction of the influences are usually consistent but the values assigned to them are considerably variable. Early in this research it was decided that general solutions would not be forthcoming from the literature or existent data sources. If a generalized solution was not available the question arose: Could a generalized technique for estimating site specific fire climate at remote sites be developed?

After consultation with USFS research personnel it was decided that obtaining one year (or season) of observations at the site would be feasible. Decision lead time and resources needed to operate stations are limiting factors. The instrumentation available would be limited to recording hygrotheromographs and air movement recorders. These time and equipment limitations constrained the approaches that could be taken. After some exploratory studies, it was decided to use stepwise regression between the one year of daily observations at the remote site and daily observations from an appropriate permanent fire weather station. By applying the equations from one year of observations to the long term records of the fire weather station, an estimate of the fire climate at the remote site is obtained.

Because of instrumentation requirements and limitations, the variables considered in this research include daily maximum and minimum temperature,

maximum and minimum relative humidities and wind speed. Relative humidity is difficult to use in this type of statistical analysis so that afternoon and morning dew points are used as a substitute. Precipitation, being a physically discrete phenomenon, is considered intractable for this research. Treatment of the spacial variation of precipitation and all other variables used in the estimation of fire hazard are beyond the scope of this research.

The major requirement of the regression technique is that it provide <u>improved</u> estimates of fire climate at a remote site over estimates using unadjusted data from a fire weather station data. Although the regression procedure uses daily data it is not required to give accurate daily estimates. It is not the behavior of a particular fire that is sought but rather the wildfire potential of the site.

Section 3 contains the description of the regression procedure. The study areas and the data are described. A brief review of the procedures is also presented although a more detailed description is presented in Part 2 under separate cover. The individual regression equations are described in terms of their gross form and performance parameters. These equations are then tested for their ability to estimate fire climate of a test year.

1.2 Specific Objectives

The two primary objectives of this research are:

1) To estimate the effects of stand changes on fire climate expressed as daily maximum and minimum temperature, maximum and minimum relative humidity and afternoon wind speed as measured by standard instrumentation.

2) To develop and test a generalized regression procedure to extrapolate weather station data to remote sites in order to improve estimates of wildfire potential (variables to be extended are daily maximum and minimum temperatures, afternoon and morning dew point and afternoon wind speed).

2. Effects of Stand Changes

That forest vegetation influences climate near the ground is intuitively obvious. Attaching values to these influences is not simple. The observational and physical studies reviewed by Kitteridge (1948) and Geiger (1966) show a wide divergence of measurements and more recent observational studies do not clarify the situation. This is to be expected because the change of observed climate following vegetative change at a site is a function of such factors as aspect, latitude, time of year, surface roughness, albedo, atmospheric stability, the distribution of remaining vegetation, and heat transfer at the ground. Approaches to this problem are being made through physical modeling but they are still in the early phases of development. Fortunately there is no need to be overly specific in specifying vegetative influences since the fire models in which the meteorological data are used are idealized. The literature is reviewed to obtain rough approximations of forest vegetation influences on standard measurements of temperature, relative humidity, and wind speed.

In this section of the report, the results are given heuristically - without many direct citations. This is in part due to the fact that the synthesis of the literature is intuitive. The following is a list of primary sources of data or ideas: Geiger (1961) and Kitteridge (1948) for excellent

reviews of previous work; Albini and Baughman (1978), Bergen (1971), Bergen (1974a), Bergen (1974b), Cooper (1965), Countryman (1955), Fons (1940), Hayes (1941), Hursh (1948), Jemison (1934), MacHattie (1966), MacHattie (1970), MacIver and Powell (1973), Morris (1941), Muraro and Hughes (1971), and Wilson (1970) are primary sources.

It would be best to describe vegetative changes resulting from management activities in terms of stand density. Unfortunately most of the studies are in terms of "uncut" and clearcut and only a few consider partial cuts expressed as a percentage cut. This report follows this pattern in that results are presented as a function of percent cut. An uncut stand is considered to be a mature stand of unspecified composition and density. In addition to percentage cut the results are differentiated for three different classes of stands. Class A (the majority of situations) covers stands that have closed or nearly closed canopies and the management activity being considered does not create holes in the canopy larger than about one tree height in diameter. Class B consists of stands that grow in an open form with large openings in the canopy (greater than about one tree height) or the management activity would lead to such canopy openings. Ponderosa pine savannah would be an example of class B. Class C consists of low dense reproduction, shrub fields or timber with overstory reaching the ground. For wind speed there may be an overstory, but for temperature and humidity no significant canopy is allowed for stands in class C. Obviously these classes are very broad and are meant to consider three widely divergent situations. The classification is not intended to be rigid and the user is free to choose intermediate values. The class to be used is that which best describes the stand at the time(s)

elapsed since treatment. Also note that the class may change in time. After a clearcut, for example, class C may first apply, then class B, and after several years class A would exist.

2.1 Wind Speed

The height above the ground that wind speeds are observed is not highly standardized. For this reason the vertical profile of wind speed must be considered before vegetative influences are considered. Most methods for doing this require the measurement of a scale parameter that is highly dependent on the nature of the ground surface. A more general and straightforward technique is given by Geiger (1966) and also Chrosciewicz (1975). By their method the wind speed at a height can be expressed as:

$$WS = bh^2$$

where WS is the wind speed at height h, b is the wind speed at unit height, and a is an empirical coefficient. For two different heights

$$WS_1 = bh_1^{\,a} \text{ and } WS_2 = bh_2^{\,a}$$

apply. Dividing these equations gives

$$WS_1 = WS_2\ (h_1/h_2)^2 \text{ or}$$

$$WS_1 = k(WS_2); \qquad WS_2 = k^{-1}(WS)$$

where $k = (h_1/h_2)^a$. Chrosciewicz (1975) determined the value of "a" to be 0.2209 for a cleared area within a slash field. Assuming this value to be constant (an adequate assumption here during the day except near the ground) and considering h_1 to be 20 ft., values of k and k^{-1} are plotted in Figure 1 as a function of the h_2, the height above an effective surface. From Stanhill (1969) the effective surface can be considered to be 0.64 times the understory vegetation height. Figure 1 pertains to daytime conditions in the

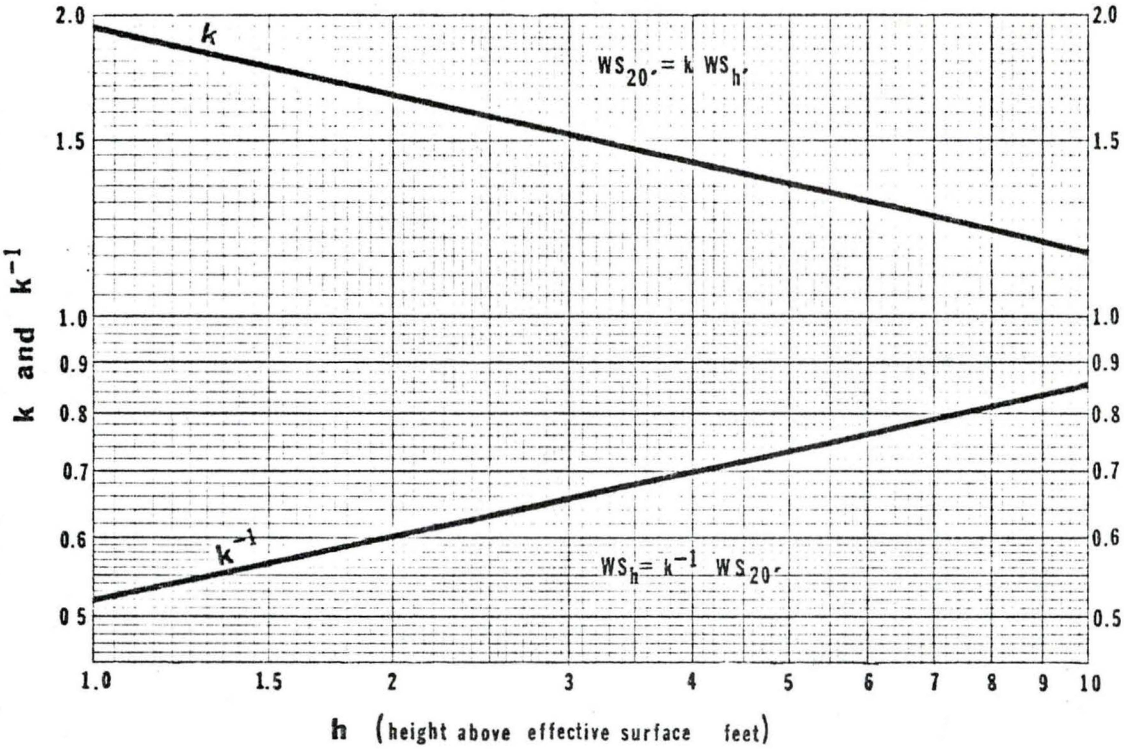

Figure 1. Coefficients for Adjusting Wind Speed with Height.

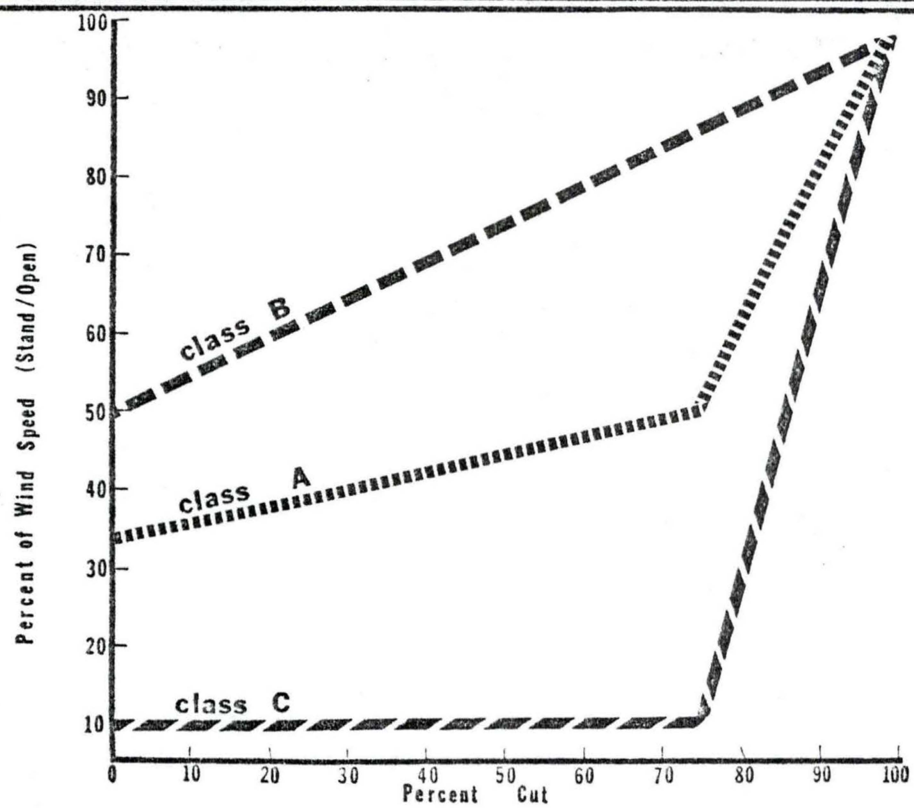

Figure 2. Ratio of Wind Speed Under Canopy to Wind Speed in Open.

open. To illustrate its use, assume that the wind speed observed at 8 ft. is 5 mph. The wind speed at 20 ft. is then 1.2 x 5 mph = 6 mph and the 3 ft. wind speed is .65 x 6 mph ≃ 4 mph. It is recognized that this procedure is not reigorously true: it has been found to be quite consistent with observation except within one or perhaps two feet above the effective surface.

The effects of vegetation and treatments are considered after adjustment for height. Figure 2 contains multiplicative values for the conversion from open to stand conditions as a function of percent cut for each of the stand classes. (To convert data from stand to open conditions use the reciprocal of the values). An outstanding feature of the curves for classes a and c is the flatness between between 0% and 75% cut. Observations strongly suggest that as long as much of the stand canopy remains and there are no large gaps, then the air below the canopy remains fairly isolated from the momentum above the tree tops (notably Cooper, 1965 and Morris, 1941) and is roughly constant with height. Within heavy foliage near the ground wind speeds are observed to be consistently below 2 mph for speeds above the canopy up to 20 mph.

Suppose that an average wind speed of 8 mph is observed at 10 feet above the ground in a clearing near a site with a mature stand. A manager wants to know what the average windspeed at 2 ft. would be if the stand is clearcut or thinned 50%. From Figure 1, the 20 ft. wind speed is 1.2 x 8 mph ≃ 10 mph and the 2 ft. average wind speed is .6 x 10 mph = 6 mph for the clearing. This is the average speed for the clearcut alternative. For the partial cut, the 2 ft. wind speed is farther reduced by a factor of .4 to 2 or 3 mph. Now suppose that the instrument is not within a clearing but within the stand and

the average windspeed is 3 mph. If the stand is randomly thinned by 50% the 10 ft. windspeed would be 1/.4 x 3 mph ≃ 8 mph and 1/.3 x 3 mph ≃ 10 mph if the site is totally cut. These speeds transform to 5 mph and 6 mph respectively at 2 ft. above the ground.

As a final example, consider a stand that has mixed areas of dense and open ponderosa pine. The highest observed wind speed at 20 ft. in a clearing is 30 mph and the manager wants to know what the corresponding wind speed is at 3 ft. The 3 ft. wind speed in the clearing would be .65 x 30 mph = 20 mph. The stand has characteristics of both class a and b so an intermediate adjustment factor for vegetation is appropriate. A choice of .4 seems valid. The 3 ft. wind speed inside the stand would be .4 x 20 mph = 8 mph.

A more theoretical approach to the same problem is taken by Albini and Baughman (1978). At the time of this writing their work is in review draft form so details are not described here. Their results are very similar in magnitude as those presented here. The form of their results is very useful for considering a large number of possible situations and/or in a computer program. Use of Figures 1 and 2 is probably easier for quickly determining a single value or a range of values for a particular site. It is suggested that the user refer to Albini and Baughman (1978) and then decide which approach is preferable.

2.2 Relative Humidity

The observations in the literature for forest influences on relative humidity are contradictory. In most of the data sets reported the changes in relative humidity are explained solely by changes in temperature. Beyond

the effects of modified temperature the situation seems to be that for most cases there is no forest influence on relative humidity but there are some notable exceptions (Jemison 1934, Hayes 1941).

A partial solution to the contradictions might be found by considering the residence time of the air in the open. If air moves across a square clearing of 50 acres at 5 mph it spends only about seven minutes in the clearing. Mixing processes within the clearing make the microscale moisture budget very complex but it is conceivable that not much net exchange of water vapor takes place in seven minutes. Also instrumentation for relative humidity is not very precise. Loss of calibration or difference of response can create or destroy small differences. The single best decision is that there is no change in relative humidity between forest and clearing except that due to change in temperature.

2.3 Temperature

Figure 3 contains additive adjustments for stand influences on maximum temperature. The three classes of vegetation are used again except that class c is more restrictive. No significant overstory is allowed in class c and brush or reproduction should provide at least 75% cover. However immature stands up to about 20 ft. to 25 in. of height can be included in class c. The main assumption of class c is that air movement is restricted but insulation is not reduced: solar energy is "trapped" within the vegetation near the instrument shelter. Stand effects on minimum temperature are about one half the magnitude of maximum temperature and have the same sign.

The adjustments for maximum and minimum temperature <u>inside an instrument</u> shelter are small and for many purposes they may be ignored. Their use

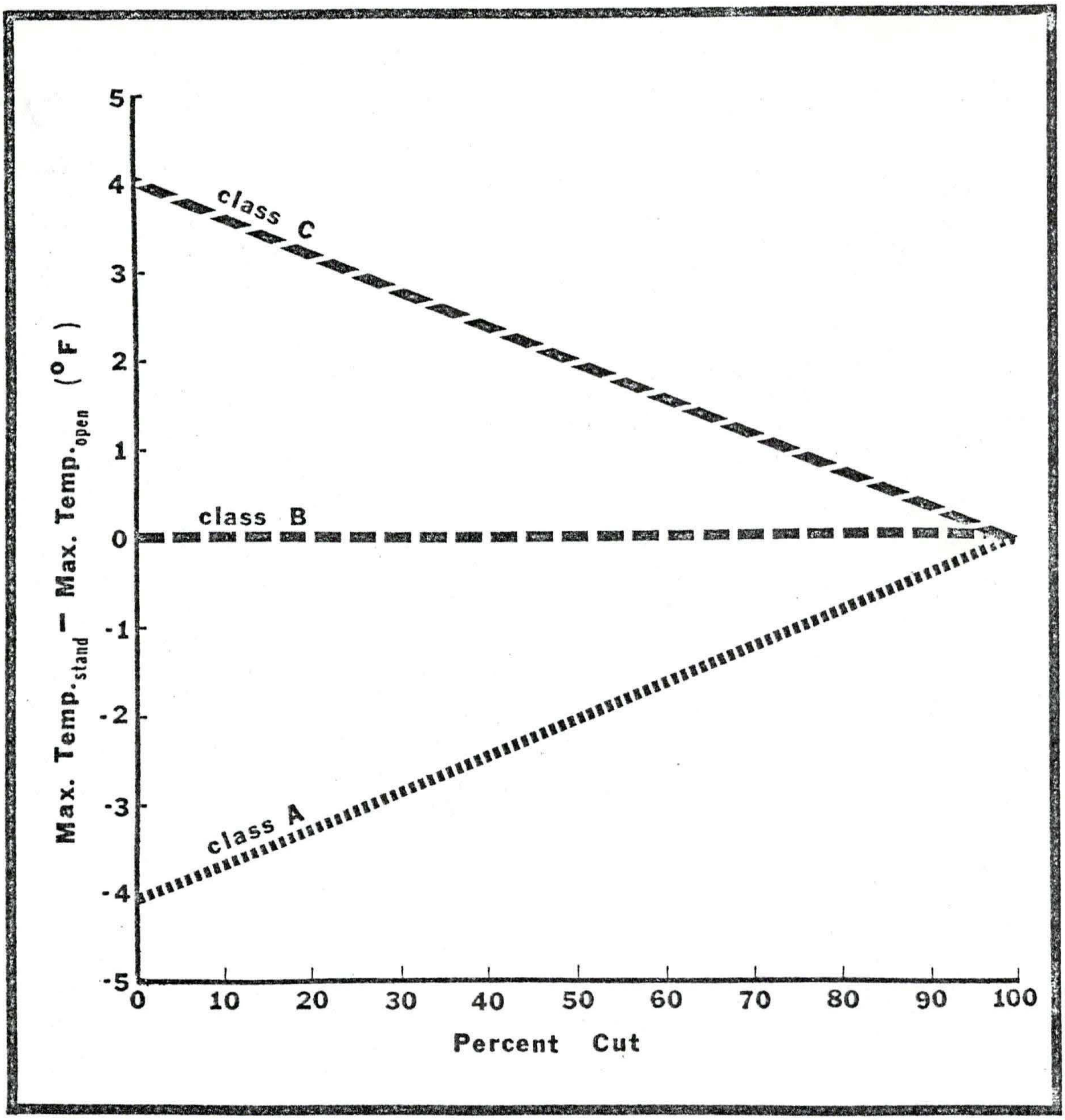

Figure 3. Effect of Canopy on Maximum Shelter Temperature.

can be justified on the grounds that they would result in a shift in the computed fire behavior parameter distributions in the right direction and therefore improve estimates.

It must be noted that the magnitude of the above changes <u>do not represent</u> very well the changes of the fuel environment. In the version of the fire hazard potential computer program available to the authors (Program HZRDFC3) fuel moistures are computed from equilibrium moisture contents and a set of coefficients. For relative humidities between 10% and 50% and cloud cover less than .5 the equation for daytime 1 hour time lag fuel moisture is

$$FM1 = 1.03(EQMC) = 1.03(2.227 + 0.160*(.75*RH) -.015*T)$$

where EQMC is the equilibrium fuel moisture, T is the observed temperature (°F) and RH is the observed relative humidity. Observations are made in an instrument shelter 4.5 ft. or more above the ground but fuels are exposed and on the ground. Often the effects of canopy are larger at the ground than at shelter height. Consider two weather stations; one in a clearing and one inside a stand. In the stand the temperature is 80°F and the relative humidity is 40% for the air both in the shelter and next to the ground. In the clearing the air is 85°F in the shelter but 120°F next to the ground. The specific humidity is the same in the clearing as in the stand but, because temperature is modified, relative humidity is 34% at the shelter and 11% at the ground. Using these values in the above equation gives FM1 = 6% at both the shelter and the ground in the stand. In the clearing, using instrument shelter observations FM1 = 5% is calculated but for conditions at the ground FM1 = 1.8% is obtained. Adjusting shelter temperature for stand changes in this example accounts for only one fourth of the change in 1 hour time lag fuel moisture.

Computation of the moisture content of heavier fuels are also affected. Accounting for changes of lapse rate near the ground resulting from management activities is more important than considering changes of shelter temperature. The former task is complex and beyond the scope of this research.

Choices required in using this material are judgements that need to be made for each site being considered. The figures contain information that is idealized and approximate and not meant to override experience and sound judgement. Nor should the material be substituted for real data when such data can be obtained.

3. Extension of Observations to a Remote Site

In a sense the preceding material accounts for differences of fire climate that result from changes of biological influences. This section treats the influences of physical factors that cause a difference of fire climate between two locations. Physiographic differences between two stations, local air circulations, the synoptic climatology of the area and the interactions between them are some of these factors. In developing statistical relationships between measurements, only samples of some of the effects of the physical influences were used. The measurements relate to the physical processes as symptoms relate to an illness. A doctor can sometimes diagnose and treat the illness by analysis of the symptoms. Other times, as with influenza, only the symptoms can be treated. Here the problem of estimating climate at remote locations in mountainous terrain is like the flu - only the observations are treated. Because a general solution to the problem is unlikely and modeling efforts are ongoing elsewhere, this research does not seek a single or a deterministic solution. Instead it seeks a procedure that can capture

the statistical (symptomatic) relationships of climate between two locations. It does not explicitly treat physical processes.

It is not difficult to determine a regression equation between two sets of observations but it may be wrong to apply it to other data. For this application feasibility limits the data to one season for each of the dependent (remote site) and independent (permanent site) variables. Is one season of data adequate to derive a statistical relationship between two locations? Does the set of permanent weather station observations include all the important variables? For two stations next to each other the answers are yes but in practical situations the answers are not so obvious. Here we assume that the answers to these questions are affirmative and recognize that, to the extent that the assumptions are false, errors of the estimates result.

There are ways to minimize the errors that may result from these assumptions. One is the judicious selection of the station locations. In other words what happens to one station, as much as possible, happens to the other station. Thus the remote and the permanent site should be in the same local air circulation system or "airshed." Since the freedom of site selection is small this may not always be possible, but choices should be made in this direction. If all important physical variables are included in the regression relationship then it would apply all year. If seasonally dependent variables (such as solar radiation, local heat budget, prevailing air masses and circulation patterns) are not included then errors result. Fortunately, fire seasons in an area are fairly well constrained to certain seasonal conditions. Limiting the observations and applications of the regression equations

to individual seasons helps to minimize the problem. For instance in the southwest there is an early summer fire season and another that begins with the onset of the summer monsoon. If data are taken during both these seasons then separate sets of regression equations can be developed from and applied to each season separately. Errors that result from assumptions which are not strictly true can be lessened but cannot be eliminated. It remains to be seen what the magnitudes of these errors are.

3.1 Data and Study Areas

Data from two study areas are used. One is the Priest River Experimental Forest (Kaniksu National Forest) in northern Idaho. The second is Woods Canyon (Coconino National Forest) area of northern Arizona. They represent two widely divergent climatic situations. They also represent differing conditions with regard to the relative placement of the permanent fire weather station (base station) and remote sites. The study areas were selected for these characteristics and because multiyear and multistation data were available.

3.1.1 Priest River Data

A data tape was obtained from personnel at the Mountain Meteorology Research Work Unit of the Rocky Mountain Forest and Range Experiment Station. These data are observations made at eight stations during the summer from 1936 to 1939. Observations consist of daily maximum and minimum temperature, maximum and minimum relative humidity and afternoon (1400 LST) wind speed. Relative humidities are not directly usable in this analysis. Therefore, maximum temperature and minimum relative humidity are used to compute the afternoon dew point. Similarly minimum temperature and maximum relative

humidity are used to compute a morning dew point (The equation used to perform this transformation is derived in Appendix A along with the transformation in graphical form). Also on the tape are a synthetically derived precipitation duration and a synthetic state of the weather code. (More data and variables were available but data quality and consistency limit analysis to these data. The state of the weather code is not used because it has values of only 0 or 2 and is not useful for this purpose). The eight stations are located in pairs at four different elevations. The bottom pair, at 2300 ft., is located on the valley floor with one station in timber and one in the open. The other three pairs are in clearings on north and south aspects at elevations of 2700, 3800 and 5500 ft. on the same ridge.

Each station is designated by a three digit number where the first two digits are the station elevation in hundreds of feet. The third digit represents cover at the bottom pair (1 or 2 with 1 designating the station in the open) or aspect at the other six stations (3 or 4 with 3 designating north aspect). Thus the valley bottom station in the open is numbered 231 and the south aspect station at 3800 ft. is 384. Station 231 was chosen to simulate the permanent fire weather station and 232 was unused. The remaining six stations are used to simulate remote stations. All stations are within about five miles of each other.

In the early stages of this anlysis it was observed that there was a gradual trend of error across the season. Thus the summer was divided into two seasons with the division between July 7 and July 8. Because the records of the early season are sometimes quite short and because the early season is not the prime fire season at Priest River, analysis of the early season was dropped. Thus the period of the year in this analysis is July 8

through September 30. With four years of data, six remote stations and five variables and treating each of these independently, the Priest River data set generates 120 regression equations.

3.1.2 Woods Canyon-Flagstaff Data

In this study area three remote stations in Woods Canyon and the fire weather station at the Flagstaff airport are used. The Flagstaff (FLG) station is at about 7200 ft. elevation. Remote station 1 has an elevation of 5000 ft. in Utah juniper, station 9 is at 6240 ft. in alligator juniper and station 20 is at 7400 ft. in ponderosa pine. All stations are in fairly level local terrain. Stations 1 and 9 are about 35 miles south of Flagstaff with station 9 slightly east of station 1. Station 20 is thirty miles south of Flagstaff and slightly east of the other two stations.

No wind data are available at the remote stations. People familiar with the area feel that the winds at these sites is well correlated with Flagstaff measurements implying that there may not be a need to apply the regression procedure to winds. The dependent variables are then daily maximum and minimum temperature and afternoon and morning dew point. For the remote stations dew points are computed in the same manner as at Priest River. The Flagstaff fire weather station data are taken from the National Fire Weather Data Library except for the humidity variable. The 2 p.m. and 5 a.m. observed dew points are used in place of afternoon and morning dew points because relative humidity measurements are frequently missing. This applies only to Flagstaff so that the independent variables of dew points do not correspond exactly to those of the remote or dependent sites.

Another problem exists with respect to the quality of humidity observations

at the remote sites. When condensation on the sensing material (human hair) occurs the instrument suffers a loss of calibration. Therefore, unless manual recalibration is frequent there can be periods of systematic errors in the data on the order of 10% relative humidity. For this reason we are advised that the humidity data taken before 1972 may not be very reliable. It must also be noted that the precipitation duration observation at Flagstaff is always missing.

In this research we have defined two fire seasons. The early season runs from April 10 through June 30. The late season, representing the summer monsoon, begins July 1 and ends September 20. A lack of consistently good data limits this analysis to four years. Early season years are 1970, 1972, 1975 and 1976 and the late seasons of 1970, 1973, 1975 and 1976 are studied. With four years for each of two seasons and with four variables and three remote stations, 96 regression equations are generated from the Woods Canyon data set.

3.2 Outline of the Regression Procedure

One regression equation is developed for each variable from a season of observations. There are three basic steps required to develop an equation. The first is an overview of the study area and data. This is followed by the determination of independent variables that may be considered in the final step. In the last step the independent variables to be used are selected and their coefficients are computed. These steps can be repeated if one pass does not produce satisfactory results.

This section contains only an <u>outline</u> of the regression procedure. The procedure is discussed fully in Part 2. In generalizing and adapting regression

techniques to this application certain statistical "liberties" are taken. These may result in errors if not properly handled. Such problems are treated in Part 2. Also some decision criteria are given in Part 2 which are not discussed in the following text.

To follow this procedure a computer is required. Also, the procedure is designed around the software of the Statistical Package for the Social Sciences (SPSS, Nie et. al., 1975). SPSS is selected because it is easy to use and available on virtually all large computers.

3.2.1 Survey of Area and Data

It is important to establish the context in which the regression equations are developed and applied. This includes getting some information of the general fire climate of the area. If, like at Woods Canyon, more than one season is to be used then it is best to make that determination early. Selection of the permanent fire weather station and establishment of the remote station is done at this step. Is the data from the best station complete? If not, can it be filled in? Data from both locations should be checked for quality and obviously bad data points should be removed. Once the user has established familiarity with the data and has compensated for obvious problems then data files can be built.

3.2.2 Development of Independent Variables

In this step all the possible independent variables are defined. The first candidates are the raw observations at the base station. Probably none of these should be eliminated although they may be transformed. Among the many transformations which are possible are operations like taking the log of a variable or raising it to an exponent.

Certain combinations of independent variables are obvious candidates for the regression equation. In this anlysis the temperature range, and the afternoon and morning dew point depressions are used. In the notation used in this research these are expressed as:

TR = TX-TN

ADPD = TX-ADP

MDPD = TN-MDF

where TR is the temperature range, TX is the maximum temperature. TN is the minimum temperature, ADP and ADPD are the afternoon dew point and depression and MDP and MDPD are the morning dew point and depression.

Once this set of independent variables is established and put on a computer file a correlation matrix is computed (SPSS procedure PEARSON CORR) and selected scattergrams are plotted. Correlation coefficients between each of the dependent variables (to be estimated) and each of the independent variables as well as between the independent variables are determined. Independent variables which have little or no correlation with dependent variables can be eliminated from computations in the third step. Also, independent variables that are highly correlated form new interactive terms. These take the form TXTR = TX * TR

and SWADPD = SW * ADPD

where SW is the transformed state of the weather code. Note that TXTR = TX * (TX-TN) = TX^2 - TX * TN so that a second order term in TX is created. Also observe that both SW and ADPD can be expected to generally increase on warm

sunny days and decrease on cool humid days. This is the reason that SW is substracted from 4 - so that its response is in the same direction as ADPD. The formation and use of interactive terms is presented in greater detail in Part 2 of this report. There are now three families of independent variables that are available for use in the next step. They are base station observations, combined terms derived from meteorological considerations and interaction terms derived from their intercorrelation. (Introduction of variables composed of combinations of observations does not really create new variables. It is merely a rearrangement of the form which they take in the regression equation. In this application they have been found to be useful).

3.2.3 Selection of Variables and Computation of Coefficients

Except for evaluation this step is done entirely with a computer using SPSS procedure REGRESSION. The reader is referred to Nie et. al (1975) for a general description of the procedure. (There is no full stepwise procedure in this version of SPSS. Most computers have an updated version that includes a stepwise method. On Control Data Corperation computers this is SPSS Version 6.5 and this is the version used in this research. Documentation to supplement Nie et. al. (1975) is usually available through the local computer center).

The software selects the terms that explain the most variance of the dependent variable and computes coefficients for those variables. The equation has the form: $Y' = B_o + B_1X_1 + B_2X_2 = \ldots$ where Y' is the estimate of the dependent variable, $B_o, B_1, B_2, = \ldots, B_n$ are coefficients and $X_1, X_2, X_3, \ldots X_n$ are independent variables. The program outputs a complete description of

the steps it followed and descriptors of how well the equation fit the data. If these descriptors indicate satisfactory equations then the procedure is ended. If not, the descriptors provide information on where problems exist and the user returns to the first or second step.

3.3 Priest River and Woods Canyon Regression Equations

The independent variables selected in the Priest River and Woods Canyon analyses are given in Tables 1 and 2. These tables also contain the number of times each independent variable is used in an equation for each dependent variable. Stations and seasons are pooled for these tables so that the maximum number of times a variable can be used is 24. Variables in the tables that are not yet defined are: PA is precipitation amount; PD is precipitation duration; WS is afternoon wind speed; ADPSQ is afternoon dew point squared; and ADPSQRT is the square root of the afternoon dew point. All the values in Tables 1 and 2 are dependent on some user supplied selection criteria (which are described in Part 2) so the numbers should be considered in a relative sense. At Priest River the equations for TN and MDP do not use variables that involve morning observations as often as might be expected. These variables are sometimes estimated primarily from afternoon observations. This is because a strong nocturnal inversion is persistent in the area which reduces the correlation between the base station and some of the higher elevation stations at night. In spite of this, Priest River equations for TN and MDP will be shown to be quite satisfactory.

Figures 4, 5 and 6 contain values of R^2 and the standard error of the estimates (SEE). Figure 4 is for Priest River, figures 5 and 6 are for the early and late season at Woods Canyon. R^2 is the linear correlation coefficient

Table 1 - Priest River

Independent Variables and Frequency of Use

Dependent Variable

Independent Variable	Wind Speed	Maximum Temperature	Minimum Temperature	Afternoon Dew Point	Morning Dew Point
WS	23	-	-	-	-
TX	4	21	12	2	6
TN	5	0	11	3	3
ADP	6	3	6	18	7
MDP	1	5	1	1	6
PD	9	13	18	10	6
TR	3	1	1	7	3
ADPD	3	1	5	0	7
MDPD	3	2	1	4	3
TXTR	1	7	9	8	6
TXADPD	2	2	8	3	5
TRADPD	4	8	6	8	8
TNADP	3	5	2	3	9
TNMDP	3	5	5	3	3
ADPMDP	0	3	2	4	5
TNADPD	5	9	5	4	10
TNMDPD	2	4	6	7	2
ADPADPD	3	16	10	5	7
Average number of variables per eqn.	3.3	4.4	4.5	3.8	4.0

Table 2 - Woods Canyon

Independent Variables and Frequency of Use

Independent Variable	Dependent Variable: Maximum Temperature	Minimum Temperature	Afternoon Dew Point	Morning Dew Point
SW	9	4	4	8
TX	11	6	3	2
TN	3	9	7	7
ADP	2	0	2	0
MDP	1	4	4	15
PA	16	5	7	3
ADPD	3	2	0	4
MDPD	3	2	2	4
TR	1	7	2	1
SWADP	5	6	2	3
SWADPD	2	3	5	7
TXTN	1	13	3	2
TXADPD	8	0	3	1
SWMDP	3	4	5	2
TXTR	4	6	4	3
TNADP	4	4	14	3
TNMDP	1	5	5	10
TNTR	6	3	11	7
ADPMDP	1	3	3	5
ADPADPD	6	2	2	3
MDPADPD	1	1	2	2
MDPMDPD	7	9	9	7
MDPTR	3	2	6	4
ADPDMDPD	3	2	2	7
ADPDTR	5	1	2	4
ADPSQ	3	3	5	3
ADPSQRT	3	3	6	9
Average number of variables per equation	4.8	4.5	5.0	5.2

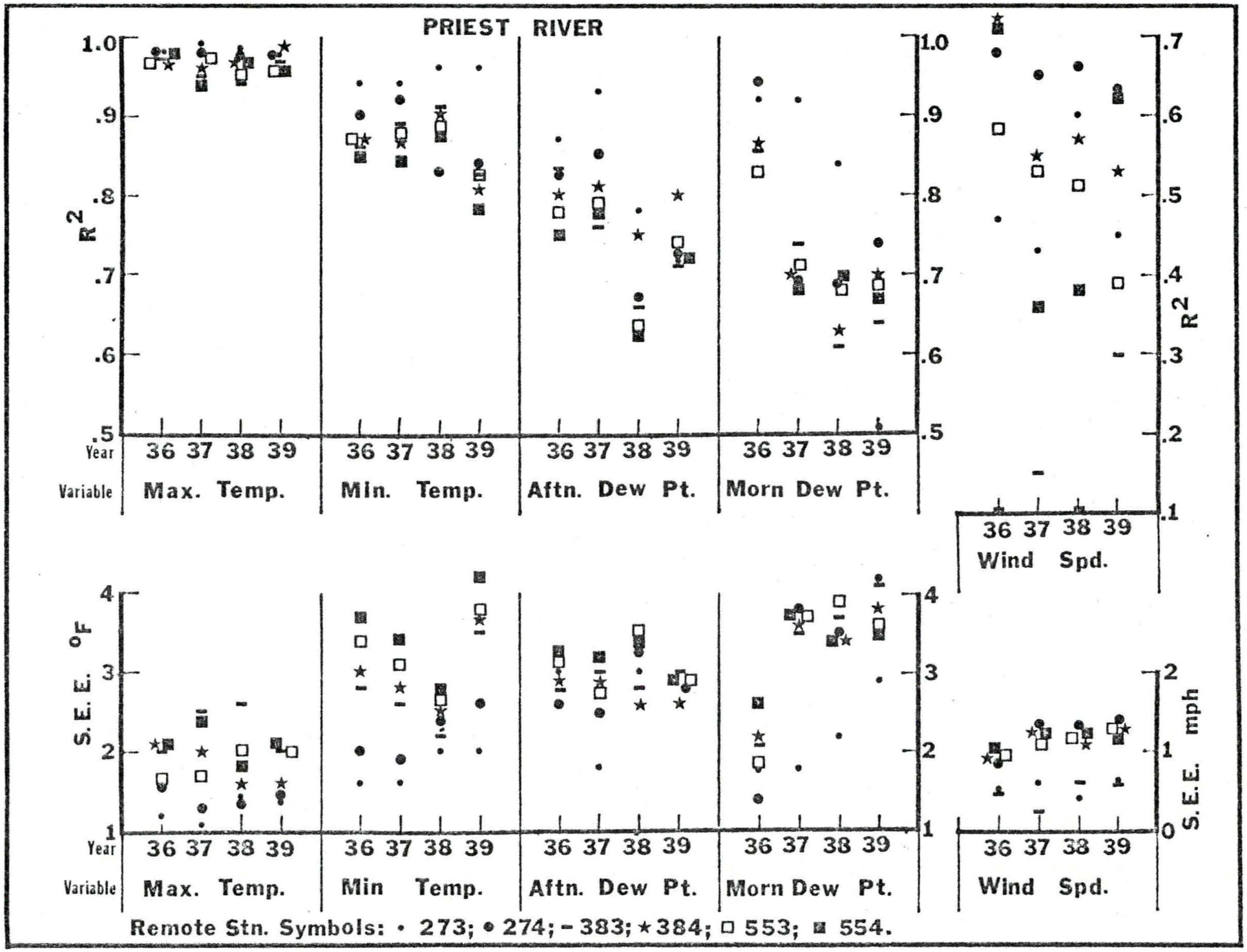

Figure 4. Priest River Regression Equation Values of R^2 and S.E.E.

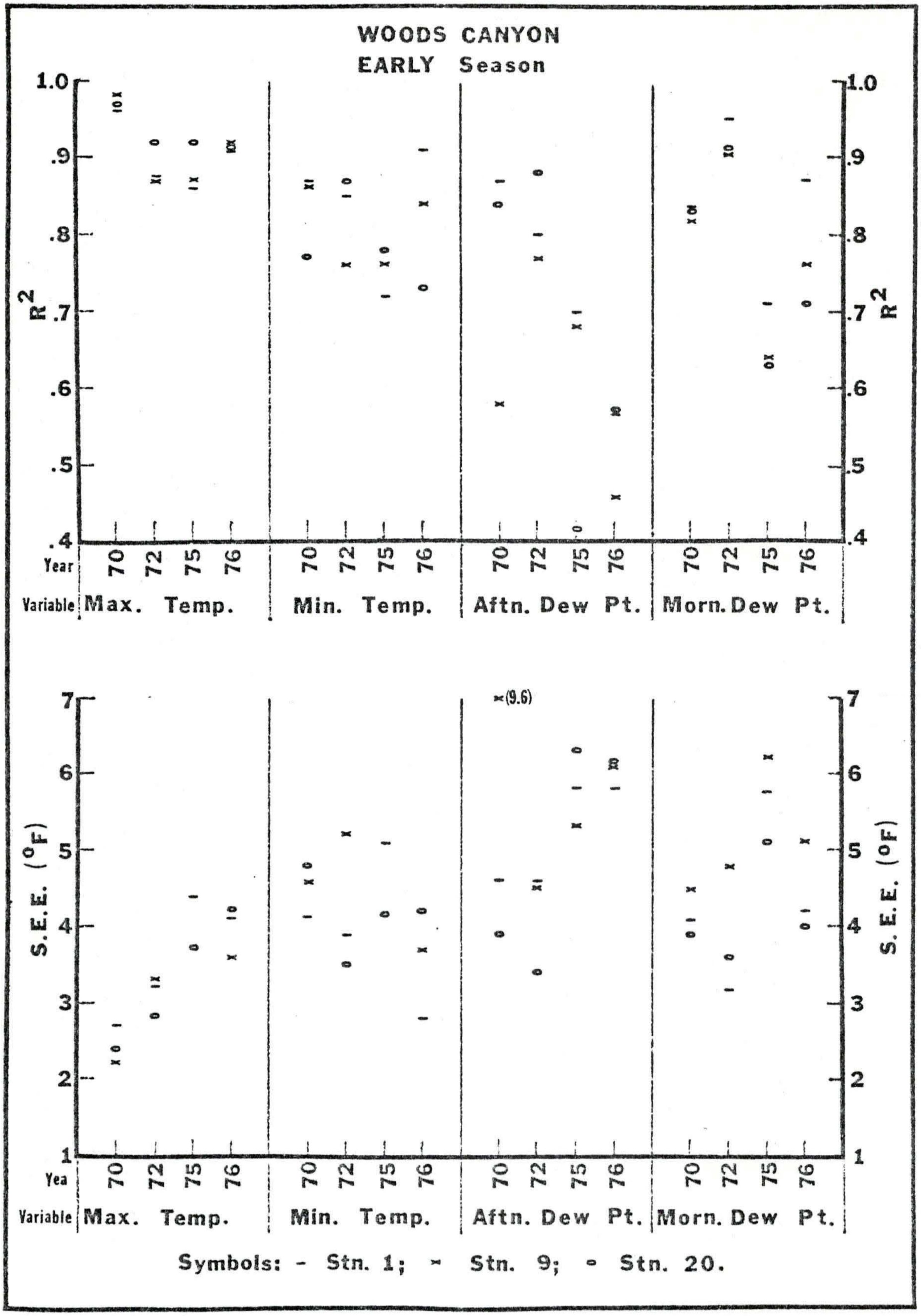

Figure 5. Woods Canyon Early Season Regression Equation Values of R^2 and S.E.E.

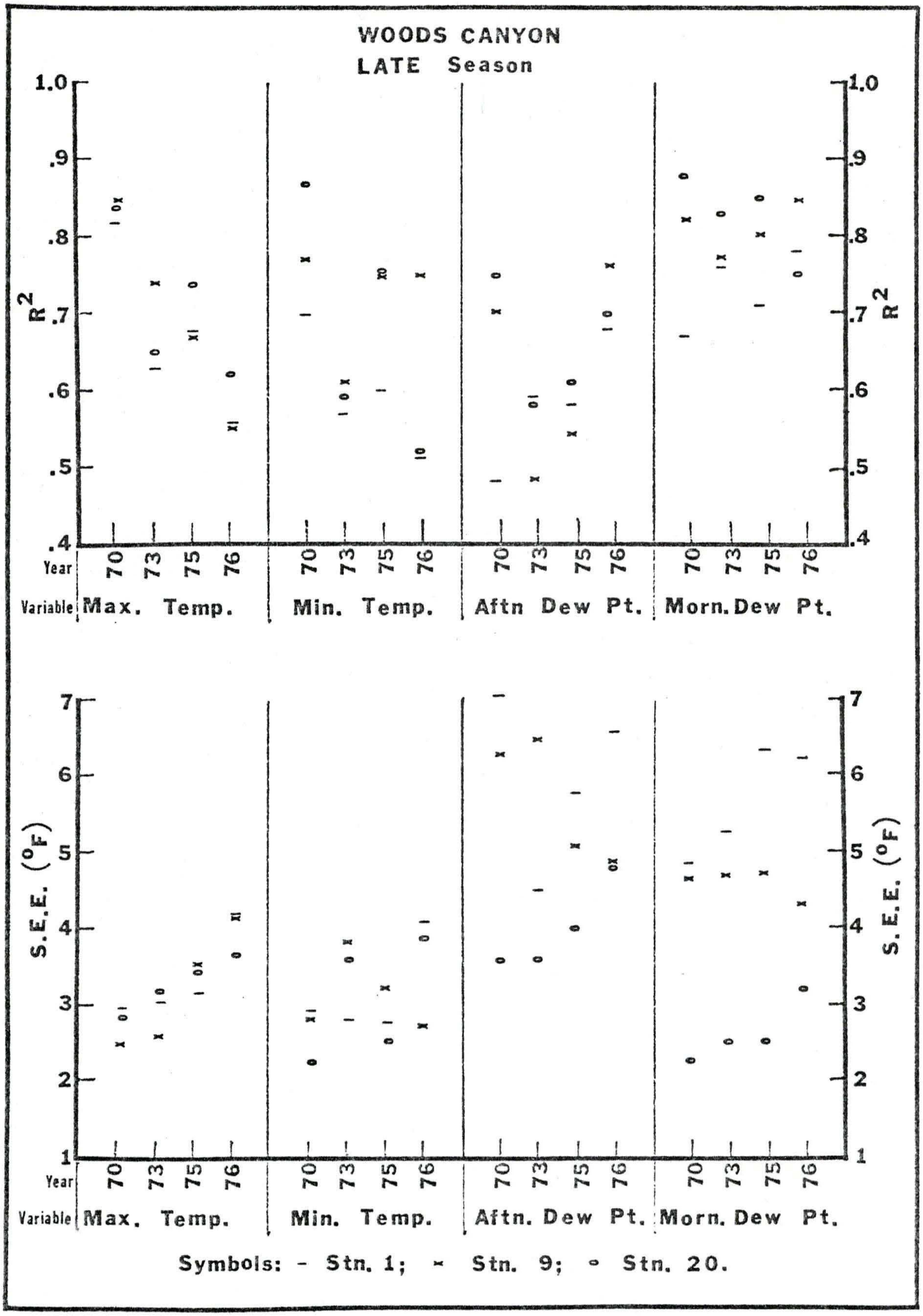

Figure 6. Woods Canyon Late Season Regression Equation Values of R^2 and S.E.E.

squared and is the fraction of the variance of the observations that is explained by the regression. The standard error of the estimate is defined by the equation:

$$SEE = (\Sigma(Y-Y')^2/N)^{1/2}$$

where Y is the observed value, Y' is the estimate and N is the number of days. If the errors are normally distributed about the regression curve then 63 percent of the residuals (Y - Y') fall within ±1 SEE and 95 percent are within ± 2 SEE. Assumption of normality is good except for maximum temperature, but even so, the first interval is roughly valid. Thus R^2 relates to the relative amount of the variation explained by the regression equation and SEE relates to the absolute amount of explained variation.

At Priest River the best equations are generated for maximum temperature. R^2 generally reduces from minimum temperature to afternoon dew point to morning dew point but SEE stays roughly even between those three. For wind speed R^2 is highly variable but SEE is always below 1.5 mph. It is peculiar that the equations for station 273 and 383 have both very low R^2 and very low SEE. This is because the average wind speed at this station is very low and doesn't vary much. R^2 is low (R^2 = 0 for a constant) but the estimates are never far from correct. To a lesser degree this is true for the wind speed equations as a group. The Woods Canyon parameters follow the same pattern as at Priest River except that R^2 is somewhat lower and SEE is greater. Recall that at Woods Canyon the dew points at Flagstaff do not correspond exactly to the synthetic afternoon and morning dew points computed for the remote stations. This likely contributes some noise to the regression relationships for those variables.

R^2 and SEE values describe the accuracy of the equations for the year

from which they are made. These statistics form a sort of benchmark to which future equations can be compared. In realistic application of the regression procedure this type of information is all that can be obtained. Those statistics do not, however, describe the uncertainty of applying the equations from one year to other years. The equation's ability to do this is considered in the next section.

3.4 Accuracy Analysis

The purpose of developing regression equations is to etimate values of climatic variables when observations do not exist. Consequently, the accuracy of the equations cannot be determined (except during the one year the remote station is operated). In using the set of equations it must be assumed that the relationships of one year are valid for other years. To the extent this assumption is not true an uncertainty of estimate accuracy exists. In this section the uncertainty is described for the two test areas.

If an equation from one year is valid during other years, then it is also true that it does not matter which year is used to develop an equation. The description of uncertainty to be presented results from applying equations from different years to a common data set and summarizing the errors which result. Specifically the Priest River equations from 1936, 1938 and 1939 are applied to the 1937 data. At Woods Canyon the test year is 1976 for both seasons. Combining stations and seasons, there are eighteen sets of daily errors for each dependent variable at each study area. The seasonal mean and standard deviation of daily errors are presented in Figures 7a and 7b for Priest River and 8a and 8b for Woods Canyon.

It is difficult to interpret these figures without an awareness of what the size of an error means in terms of fuel moisture. First note from Figure A-1 in Appendix A that at 80°F and 20% relative humidity, a difference of 5°F in dew point implies a 4% difference of relative humidity (probably within measurement error). A set of these estimates is given in Table 3.

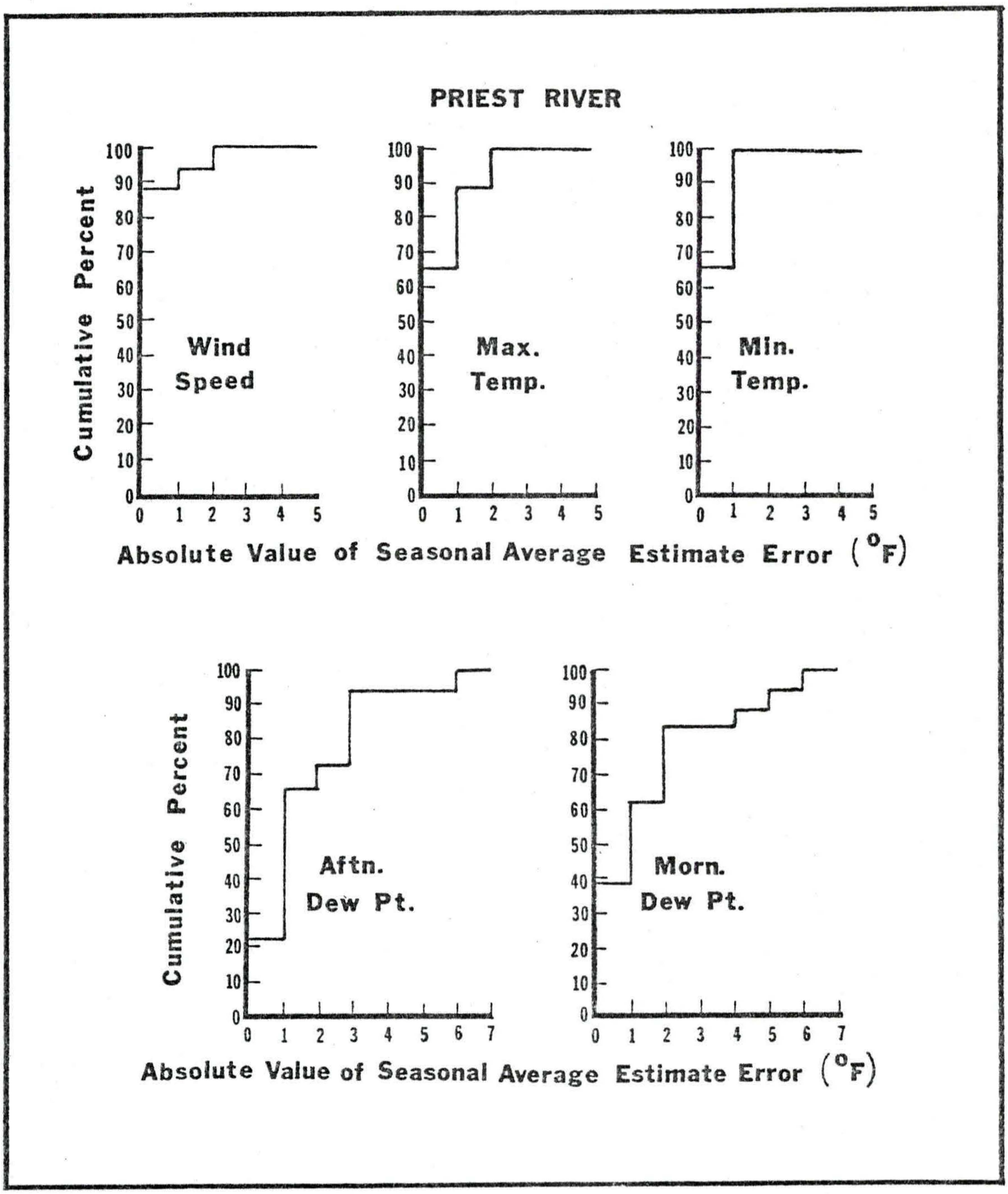

Figure 7a. Priest River Cumulative Percent of the Absolute Value of Seasonal Average Estimate Error.

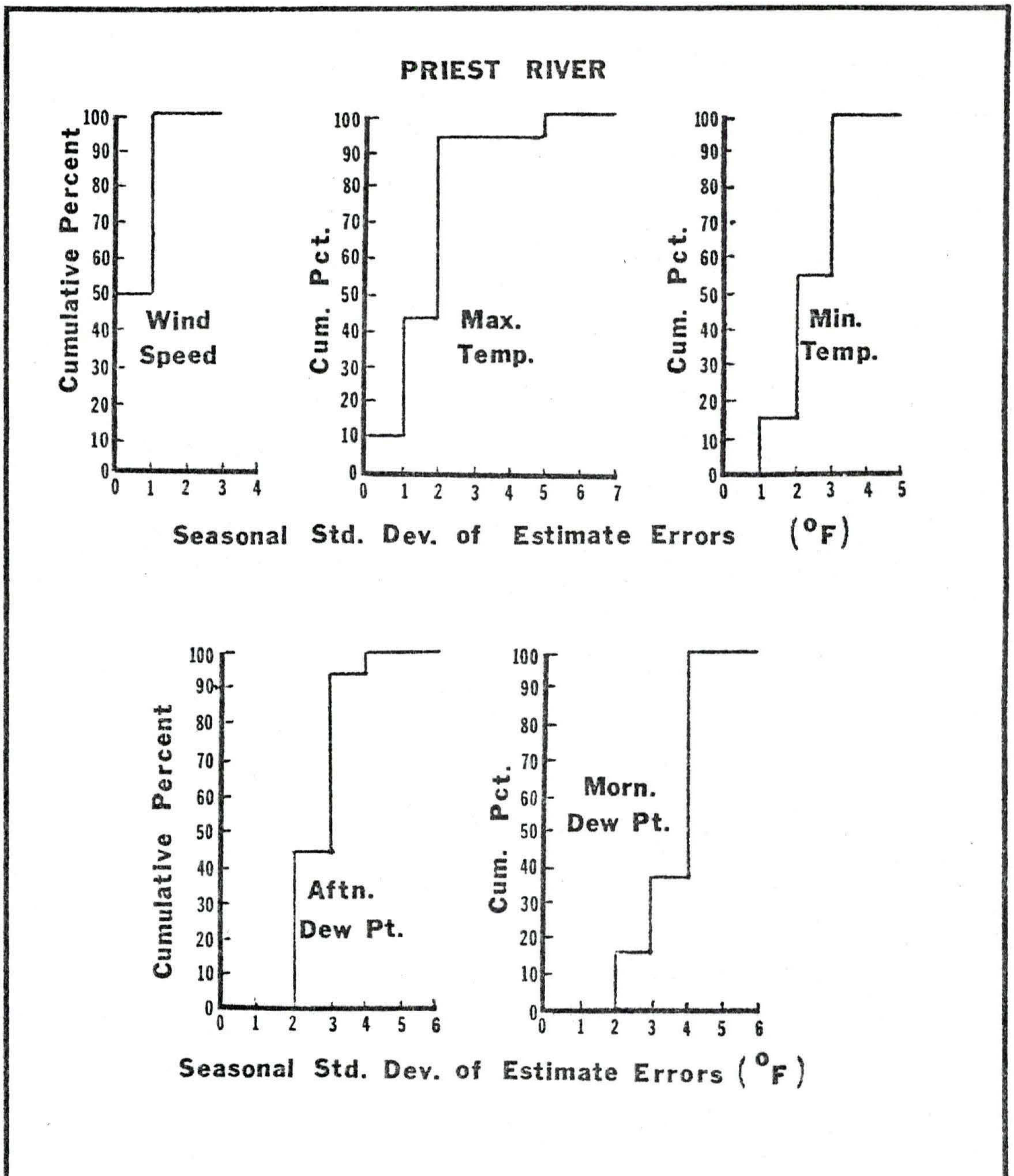

Figure 7b. Priest River Cumulative Percent of Seasonal Standard Deviation of Estimate Error.

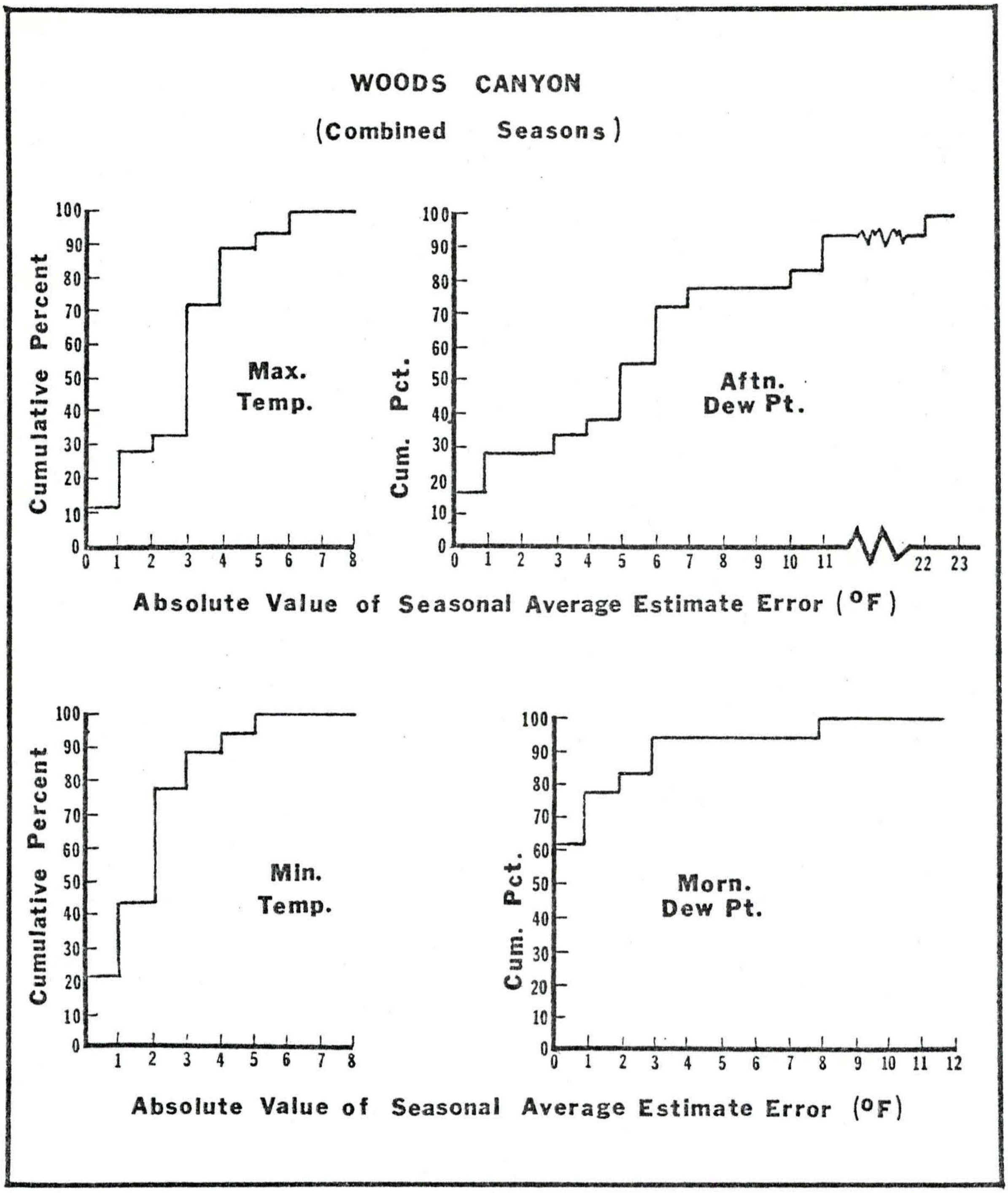

Figure 8a. Woods Canyon (combined season) Cumulative Percent of Absolute Value of Seasonal Average Estimate Error.

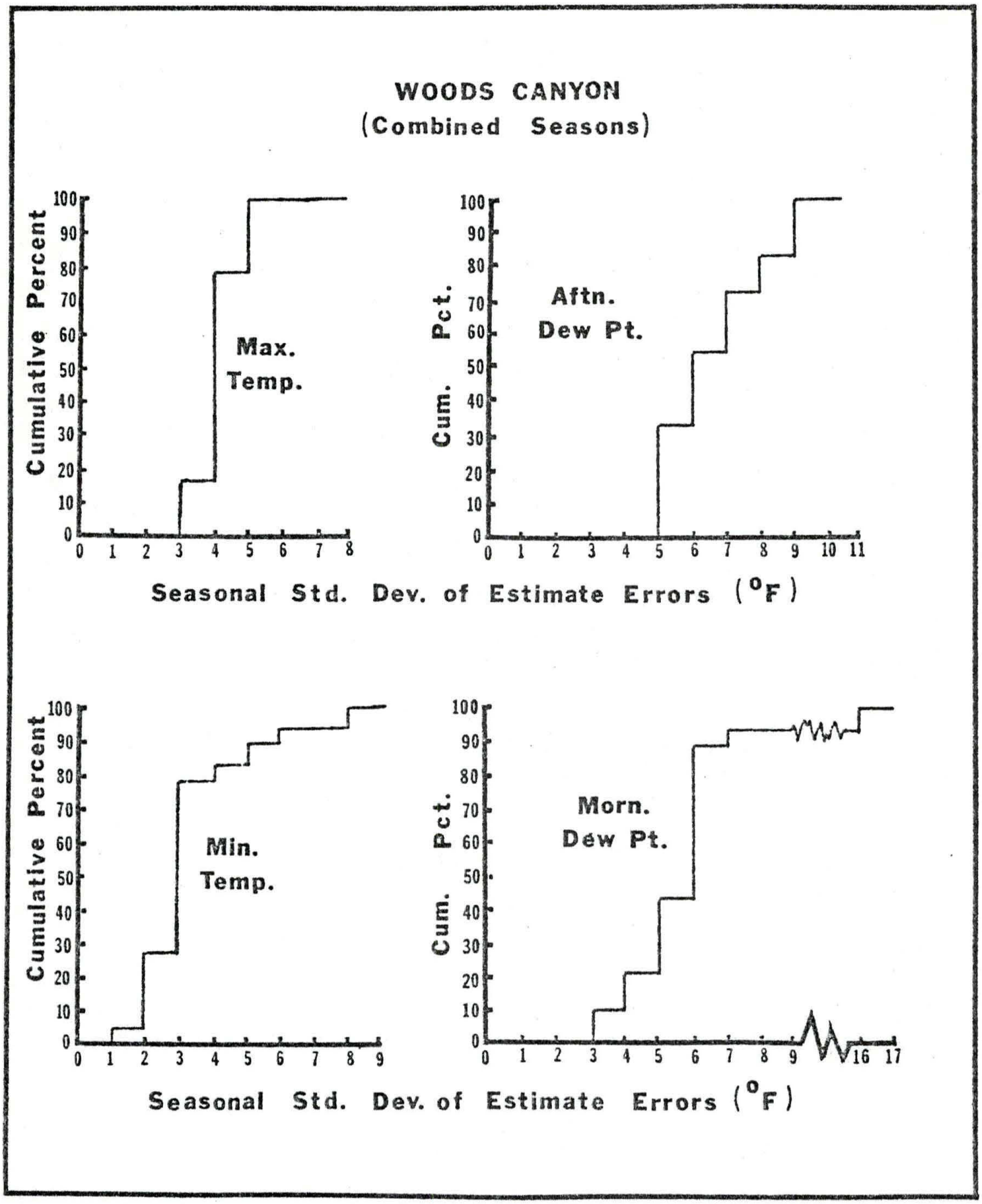

Figure 8b. Woods Canyon (combined season) Cumulative Percent of Seasonal Standard Deviation of Estimate Error.

Table 3. Magnitudes of Relative Humidity Estimate Errors from Dew Point Errors

Temperature	Relative Humidity	Dew Point Error	Largest Relative Humidity Error
80°F	20%	± 5°F	4%
80°F	20%	± 10°F	9%
80°F	50%	± 5°F	10%
80°F	50%	± 10°F	23%
49°F	50%	± 4°F	7%
40°F	50%	± 5°F	12%
40°F	90%	± 3°F	10%
40°F	90%	± 5°F	16%

During high fire danger conditions even 10°F errors of dew point imply fairly small errors relative humidity. This is not true for cooler moister conditions which influence the moisture content of all fuels at night and heavy fuels during the day.

At Priest River all of the seasonal average errors for wind speed are always less than 2 mph. Average maximum temperature error is always less than 3°F for maximum temperature and 2°F for minimum temperature. About 90% of average afternoon and morning dew points are within 5°F. From Figure 8a the average errors for each variable except morning dew point are considerably larger at Woods Canyon than at Priest River.

If estimates of TX = 80°F and ADP = 40°F (RH = 24%) are generated but the real values are TX = 85°F and ADP = 35°F (RH = 18%), then the estimated EQMC is 5% and is high by 1% of dry fuel weight. There is no great concern, then, about the size of the random component of errors (standard deviation) except for Woods Canyon dew points. Even so, the seasonal average errors are more important; particularly for the dew points at Woods Canyon.

The seasonal average estimate error is plotted against the seasonal observation average's deviation from the test year at the remote station in Figures 9 (Priest River) and 10 (Woods Canyon). At Priest River, the test year is the one with the lowest temperatures and highest dew points. This accounts for their differences along the X axis. There is no correlation of mean error and seasonal observation average deviation for the temperature variables, but a correlation seems to exist for the dew points. However, only three of the thirty-six equations for dew points result in average error greater than 4.1°F. The correlation at Woods Canyon is far more striking. Points for the temperature variables are tightly clustered about the line Y = X, but the dew point equations have points spread out along that line. These points are of great concern.

It is important that no such correlation exists between seasonal average estimate error and seasonal observation average deviation from the test year at the base station. In other words, what is happening at the remote sites is not always happenign at the base station. (For reference, seasonal averages for the base and remote stations are portrayed in Appendix B).

The dew point variables at Woods Canyon can be considered as the paradigm of this problem. There is no strong relationship between the magnitude of the seasonal average estimate error and station or year. There are five data points with average estimate error greater than 10°F. These are all 1970 and 1972 (none in 1975, and 1976 is not applicable) at two of the three stations (1 and 9). This arrangement can easily happen by chance. Also, in the one case where the same variable and season are involved, average estimate errors are radically different (11.5°F and -11.2°F. Remember that the three remote stations are within 6 miles of each other and 30-35 miles from the base station. If they do not correlate with the base station, they might be expected to cor-

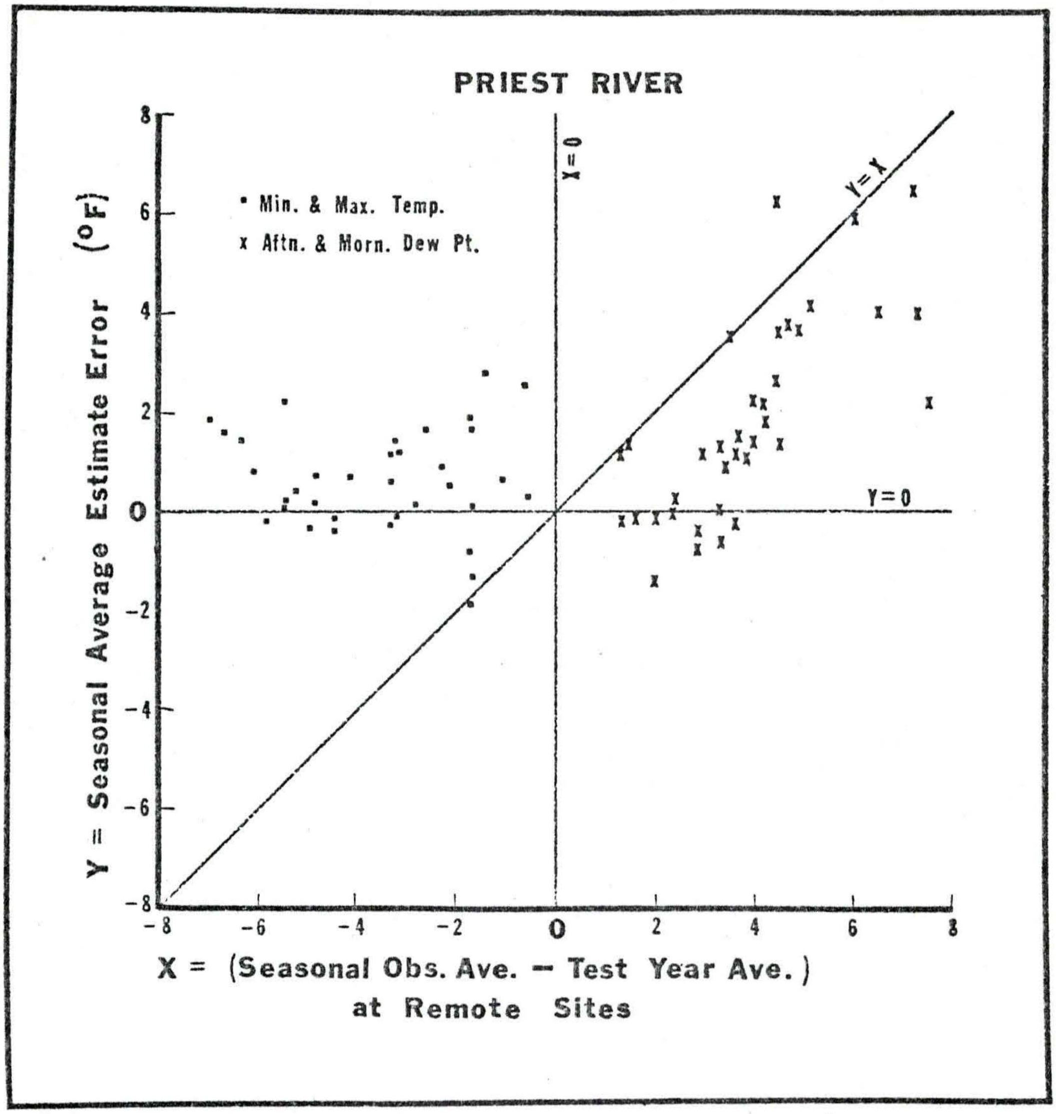

Figure 9. Priest River Scattergram of Remote Station Deviation of Seasonal Average of Observations from the Test Year and Seasonal Average Estimate Error.

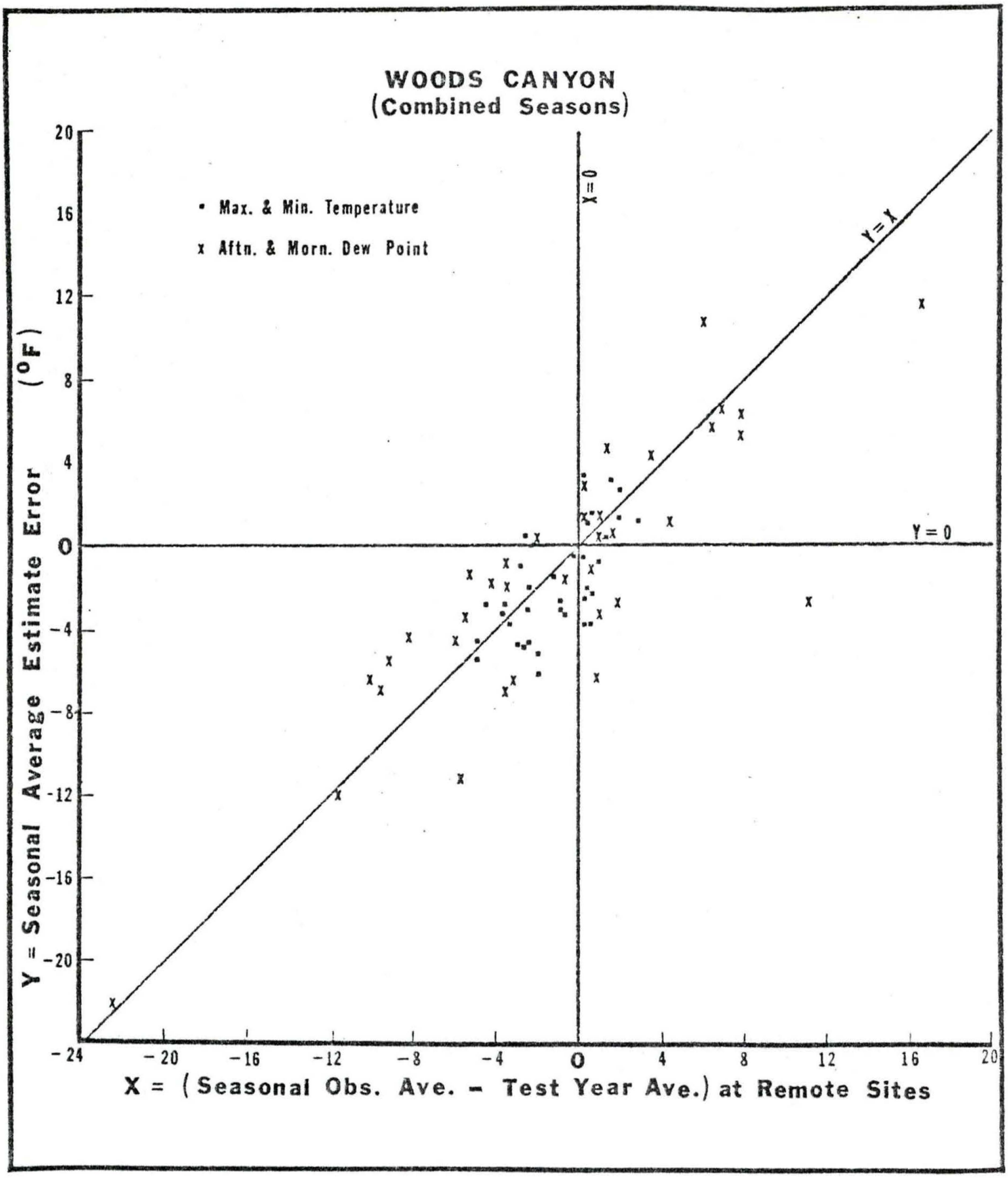

Figure 10. Woods Canyon Scattergram of Remote Station Deviation of Seasonal Average of Observations from the Test Year and Seasonal Average Estimate Error.

relate with each other. This is always not true. Since the seasonal average estimate error does not seem to be related to year or station, what does create the relationship shown in Figure 10?

The answer is not clear. There are two basic kinds of explanations. One is that there are, in a given year for a station, observation errors that do not occur in other years or at other stations. The other involves the possibility that the stations are not meteorologically related to the base station and each other in all years. There are arguments for and against either choice.

Arguments for the instrument error possibility include the observation that there are no outstanding bad years or bad stations. The fact that average observations of dew point at the three remote and nearby stations do not correlate much better with each other than with Flagstaff also supports this argument. The warning we were given about the quality of humidity observations before 1972 is also supportive. (Actually, we removed a few obvious outliers in all years. Removal of a few outliers does not necessarily imply that the data are not generally good.) But 1972 estimates are roughly as good as 1970. All but five of the average errors fall within what could be considered expectable relative humidity errors ($\approx$10%) under field conditions. Of those five, only one is clearly too large to have a major component of the error explained by this magnitude of observational error. The argument that field observation conditions explain at least a major component of the correlation cannot be ignored.

The possibility that the climatological relationships between Flagstaff and the remote stations are not constant is real. The remote stations are each in a different cover type and, to the extent that vegetation changes with climate,

the stations are in different climatic zones. The large seasonal average errors do occur at the two stations below the ponderosa pine zone. However, the three remote stations are in the same airshed and they are not always highly intercorrelated. Furthermore, if regression relationships are poor, then the seasonal standard deviation of the estimate errors may be expected to be large. These standard deviations are not proportional to the average error. (Compare Figures 4, 5, and 6 with Figures 7b and 8b).

No clear choice between these explanations seems possible. Regardless, it seems that the user of the regression procedure must accept some risk of error. This risk was described for the two study areas in Figures 7 and 8. The Priest River and Woods Canyon areas likely represent near best and near worst conditions of reasonable application.

(Some fire managers may have a special interest in the accuracy of the regression equations on extreme days. These have been examined independently for each variable and the results are presented in Appendix C).

4. Summary and Recommendations

Approximations of vegatation influences and effects of forest management activities on wildfire potential are presented in Section 2. Wind speed at flame heights under untreated canopies are about .05 to .3 of those observed at 20 ft. above the ground in the open. After stand treatment or in the open the ratio can increase to 0.5 or 0.6. Changes of relative humidity can be considered to vary only with changes of temperature. Maximum temperature is normally 4°F cooler under a canopy but can be about 4°F warmer in tall brush or reproduction. Adjusting temperature and relative humidity at the instrument shelter accounts for only a small portion of the difference in fuel moisture which results from a difference of canopy (especially for small fuels). Errors result from the fact that surface to shelter lapse rates are a function of vegetation (as well as aspect, latitude, etc.) can be very important to the prediction of fire behavior. It is strongly recommended that this factor be incorporated into the computation of fuel moistures. If research is needed to accomplish this, then it should be conducted.

A procedure for estimating values of climatic variables at remote sites was developed and tested. The procedure determines the relationship between two sites from one year of observations and then applies that relationship to the long term records at one of the sites. Because there is no way to verify the accuracy of the equations in years other than the one from which the relationships are determined, the user must accept an unknown level of uncertainty of estimate accuracy. The magnitude and character of the uncertainty at two test areas have been examined and was found to be small except for morning and afternoon dew point estimates at Woods Canyon. In these

cases the uncertainty arose from the failure of the correlation between two sites to remain constant from year to year. It is unclear if this failure is due to real physical processes, to observation difficulties or to a combination of both. If the uncertainty is due to instrumentation then it can be greatly reduced by increasing data quality. If it is a result of physical variability then not much can be done. In this case and for the worst years, estimates probably would not be worse than using unadjusted base station data but this cannot be guaranteed. If the user feels that regression estimates are atypical for the remote site or the fit of the equation during the observation years is poor then a second year of observations is warranted.

The regression procedure is applied to and tested for model input variables independently. In reality, these variables are not independent. With respect to wildfire potential estimation they are strongly interactive. As a result, the ability of the regression procedure to improve estimates of expected seasonal fire behavior has not been specifically tested. The regression procedure should be applied to simulated fire hazard assessment problems at Priest River and Woods Canyon. By using remote station, base station and regressed estimates of fire climate, improvements that result from the use of the regression procedure can be determined. Better estimates of the utility and uncertainty of applying the procedure can be established.

In this research unnormalized data and coefficients have been used. Normalizing the data may eliminate some bias in the estimates. If any bias exists in the estimates used in this work, it is small. Normalized regression coefficients are easily obtained and calculations of the estimates are only slightly more complicated than for unnormalized coefficients. It may then be preferable to use normalized data and coefficients in future work.

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Appendix A

Relative Humidity Transformation to Dew Point

Hess (1959) defines the dew point, T_d, as the temperature to which air must be cooled to become saturated during a process in which pressure and the mixing ratios of water vapor are kept constant. An equation for the saturation vapor pressure as a function of temperature (Clausius-Clapeyion equation, Hess, 1959) is:

$$\frac{de_s}{e_s} = \frac{m_v L_e}{R^*} \frac{dT}{T} \tag{1}$$

where e_s is the saturation vapor pressure, m_v is the molecular weight of water vapor, L_e is the latent heat of evaporation, R* is the universal gas constant and T is temperature. Assuming the latent heat is a neglibable function of temperature, integrating equation (1) from T = 273 to T:

$$\int_{6.108\text{mb}}^{e_s} \frac{de_s}{e_s} = \frac{m_v L_e}{R^*} \int_{273^\circ\text{K}}^{T} \frac{dT}{T}$$

$$\ln \frac{e_s}{6.108} = \frac{m_v L_e}{R^*} \left(\frac{1}{273} - \frac{1}{T} \right)$$

$$T = \left(\frac{1}{273} - \ln \frac{e_s}{6.108} \frac{R^*}{m_v L_e} \right)^{-1} \tag{2}$$

R* = 1.986 cal/mole °k, m_v = 18.016 grams/mole and L_e = 590 cal/gram. T is in degrees Kelvin and e_s is in millibars. The actual vapor pressure is (e) approximately the saturation vapor pressure at T_d and

$$e \doteq .01 * H * e_s \tag{3}$$

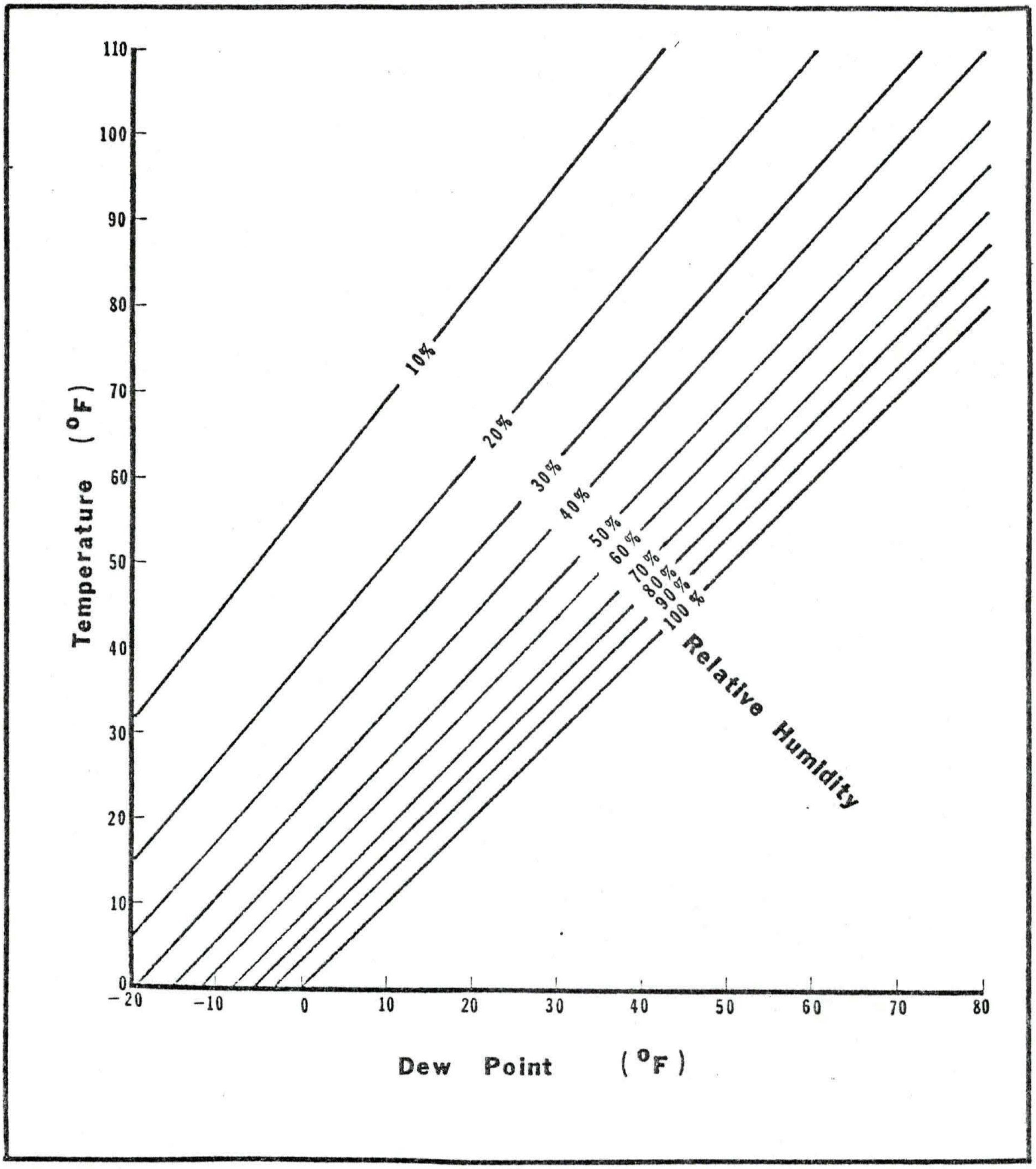

Figure A-1. Relative Humidity-Dew Point Conversion.

where H is the relative humidity in percent. Substituting (3) into (2) for e_s and inserting values of the constants gives the equation for dew point as a function of saturation vapor pressure ($e_s = f(T)$) and relative humidity:

$$T_d = (5352.2/(21.4 - \ln(0.01*RH*e_s))-273.16 \qquad (4)$$

in degrees Celsuis.

The saturation vapor pressure is a function of temperature only. Tetens equation, as given by Murray (1967), for the saturation vapor pressure over water is:

$$e_s = 6.108 \exp[a(T - 273.16)/(T-b)]$$

where T is in degrees Kelvin, a = 17.269 and b - 35.86.

Equation 4 is given in graphical form in Figure A-1. It can be used either to convert relative humidity to dew point or dew point to relative humidity.

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Appendix B

Seasonal Averages at Base and Remote Stations

Figures B-1, B-2, B-3 contain seasonal averages of primary variables at the base and remote stations. Priest River graphs (Figure B-1) are segregated by north and south aspect remote stations with the base station (231) plotted on both sets. Figure B-2 contains the early season averages at Woods Canyon-Flagstaff and Figure B-3 contains late season values. For reference, station numbers and elevations are listed below.

Priest River		Woods Canyon	
Station No.	Elevation	Station No.	Elevation
231 (base stn.)	2300 ft.	FLG (base stn.)	7200 ft.
273	2700 ft.	1	5000 ft.
274	2700 ft.	9	6240 ft.
383	3800 ft.	20	7400 ft.
384	3800 ft.		
553	5500 ft.		
554	5500 ft.		

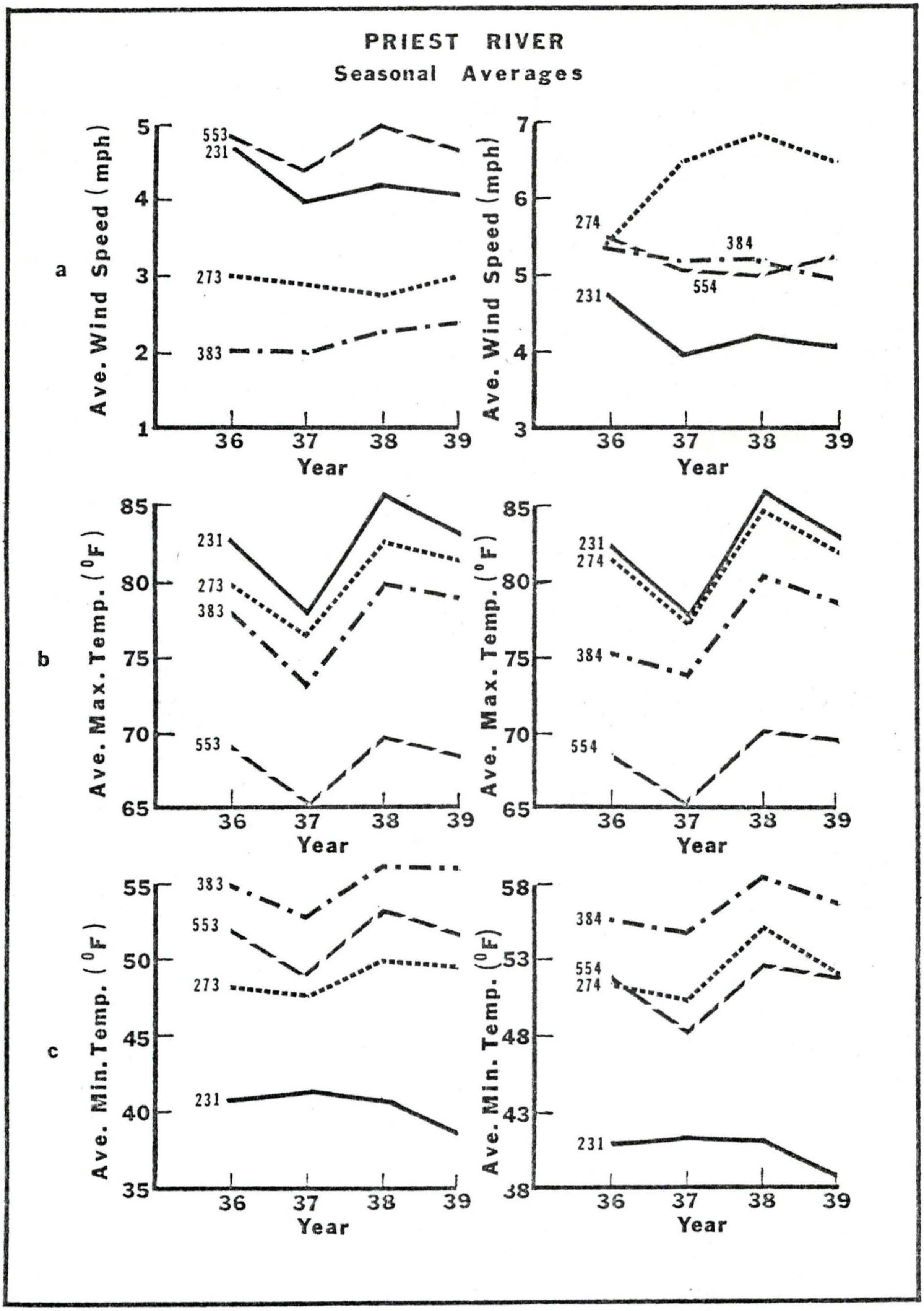

Figure B-1a,b,c. Priest River Seasonal Averages of: (a) Wind Speed; (b) Maximum Temperature; (c) Minimum Temperature.

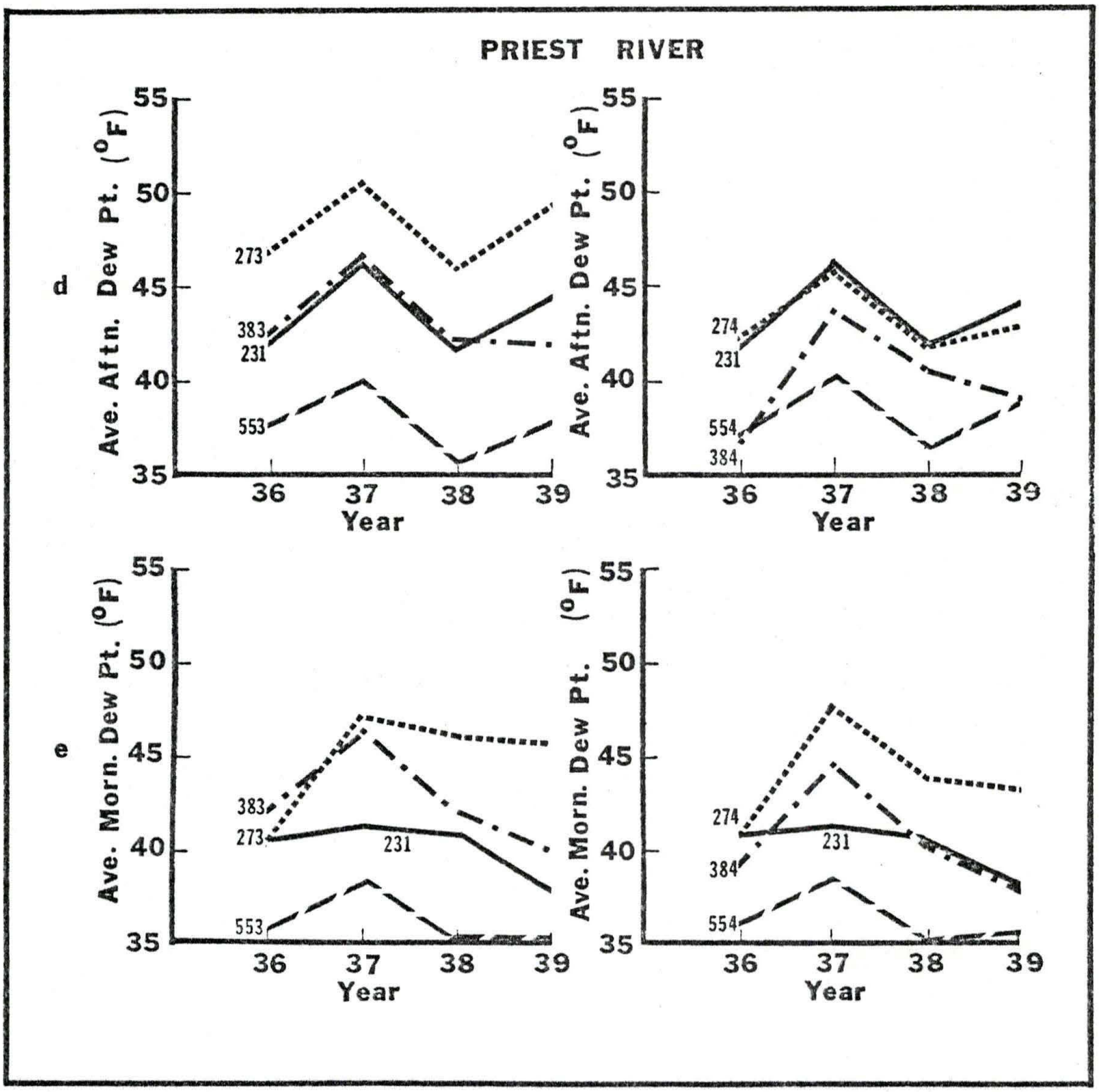

Figure B-1d,e. Priest River Seasonal Averages of: (d) Afternoon Dew Point; (e) Morning Dew Point.

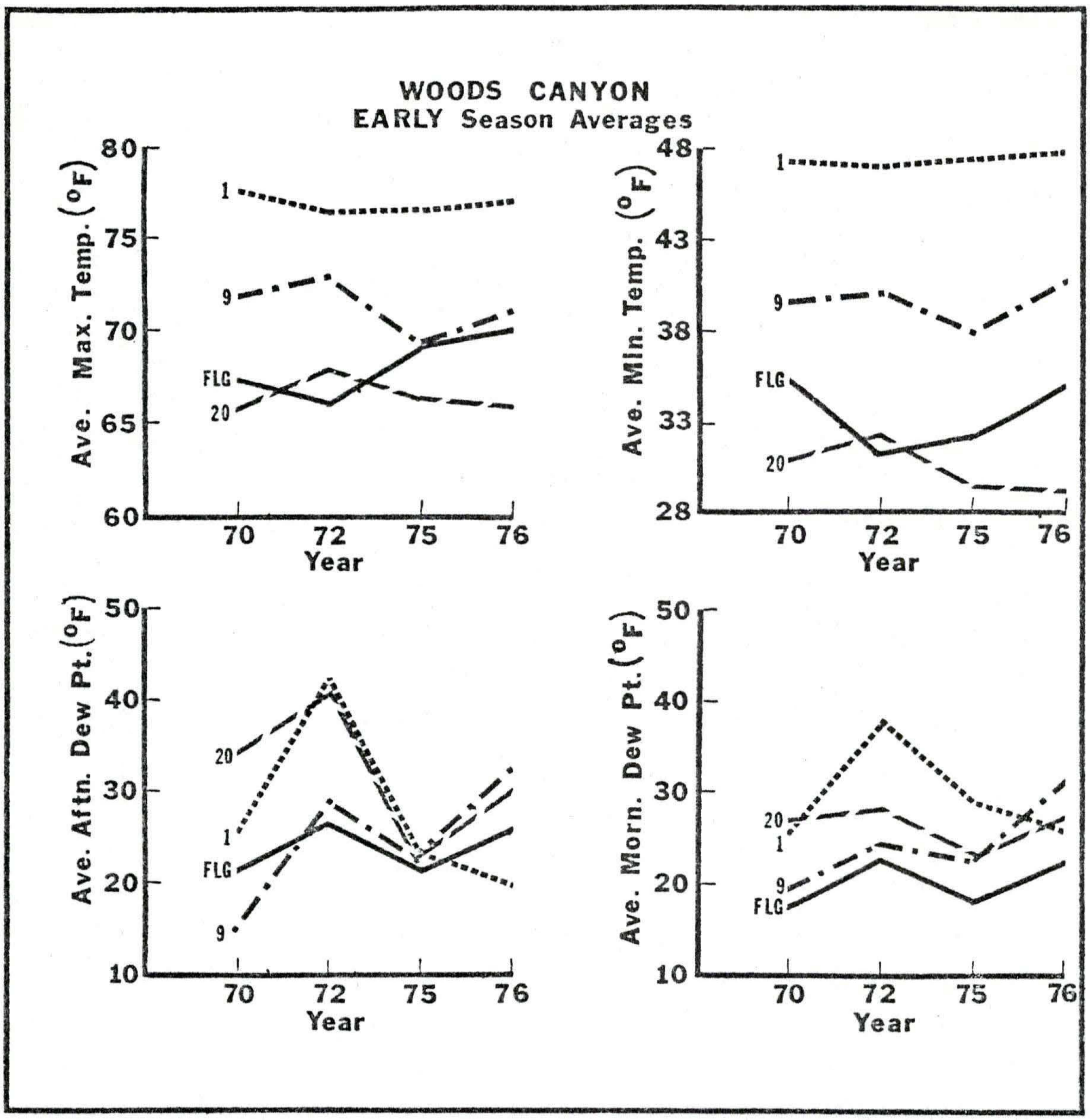

Figure B-2. Woods Canyon Early Season Averages.

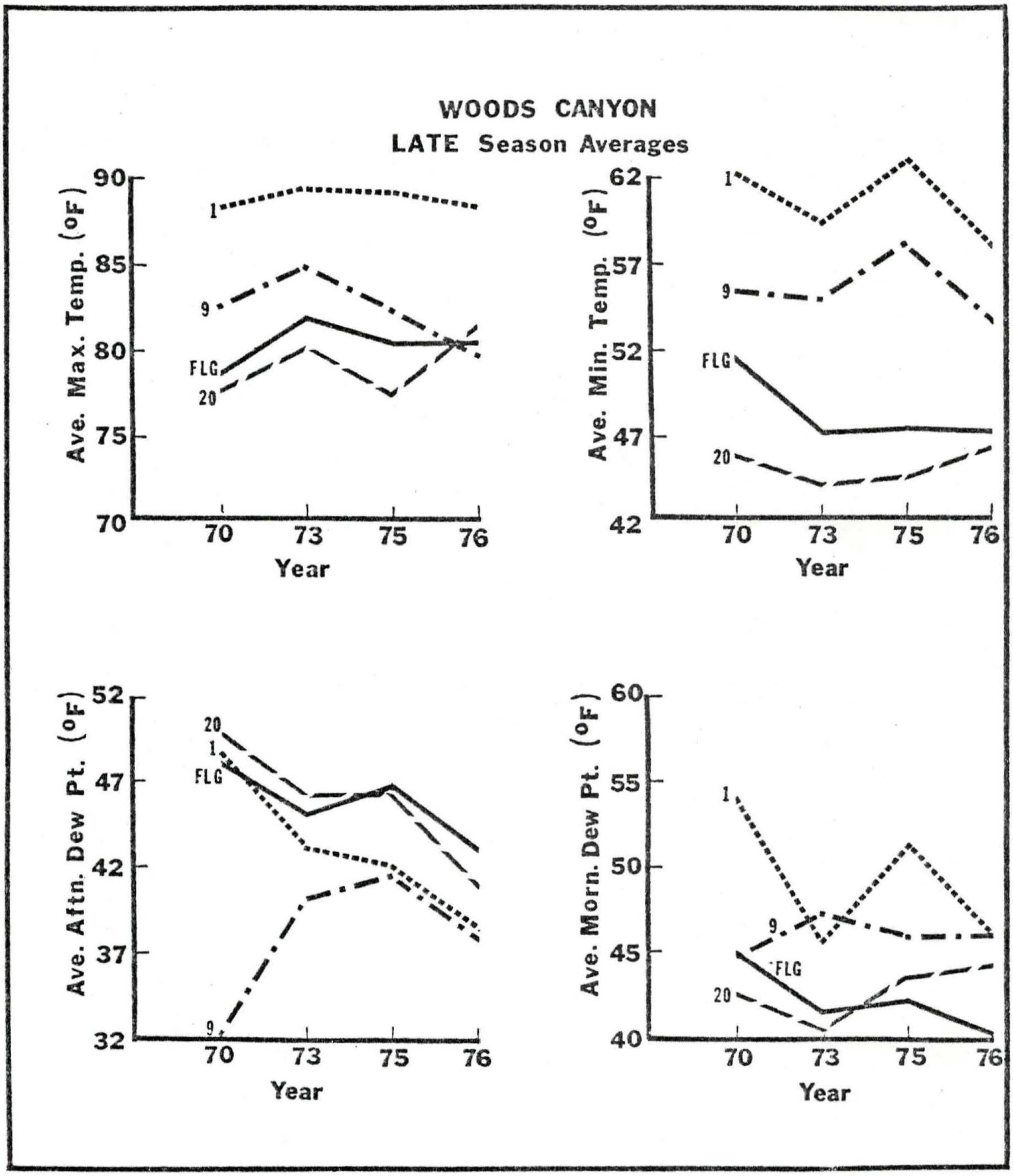

Figure B-3. Woods Canyon Late Season Averages.

Appendix C
Extreme Day Accuracy

To examine the accuracy of the regression equation on extreme days, the four highest maximum and minimum temperatures and lowest afternoon dew points during the test year at the remote stations are isolated. The estimates for these days from the regression equations developed from non-test years are subtracted from the observed values. (The extreme days do not represent extreme fire situations which result from joint events of high winds and low fuel moistures and often take several days to develop.) The results are presented in Figures D-1 (Priest River) and D-2 (Woods Canyon).

Although it is not universal, there is a strong tendency for the estimates to be less extreme than the observations. This is to be expected because if there is any variance left unexplained by the regression, it will estimate toward the middle of the scatter. The mean component of these estimate errors has not been removed. Nevertheless, the Woods Canyon results for minimum temperature and afternoon and morning dew points are disappointing. At Priest River the results seem satisfactory.

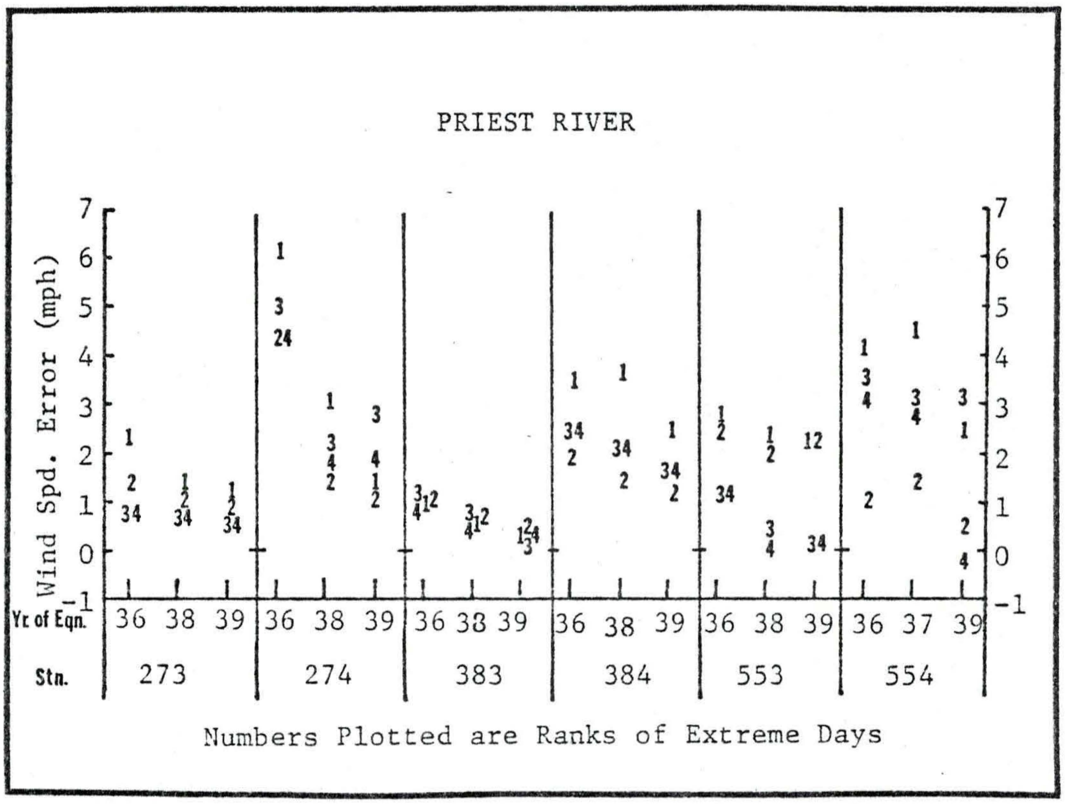

Figure C-1a. Priest River Extreme Day Accuracy-Wind Speed.

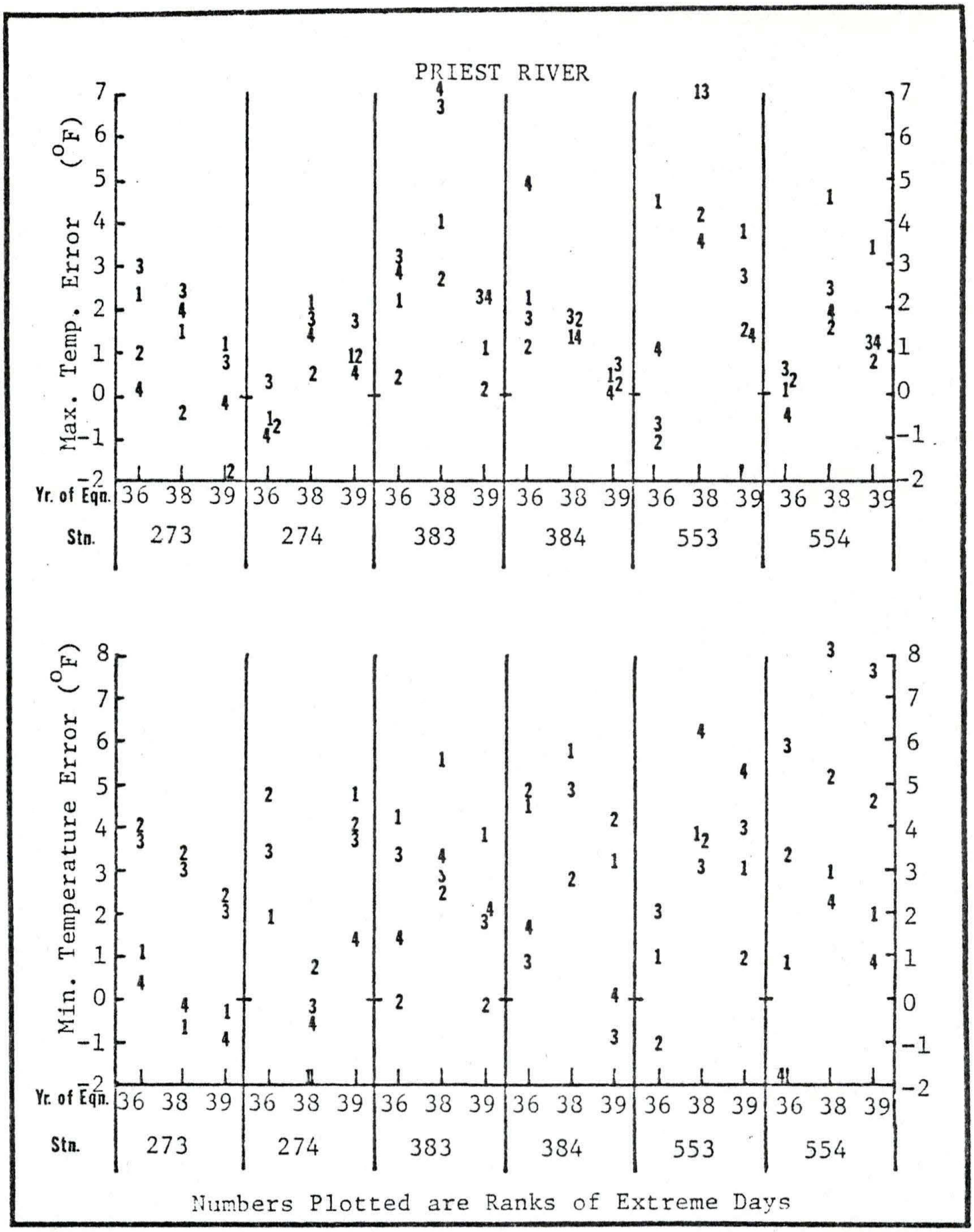

Figure C-1b,c. Priest River Extreme Day Accuracy: (b) Maximum Temperature; (c) Minimum Temperature.

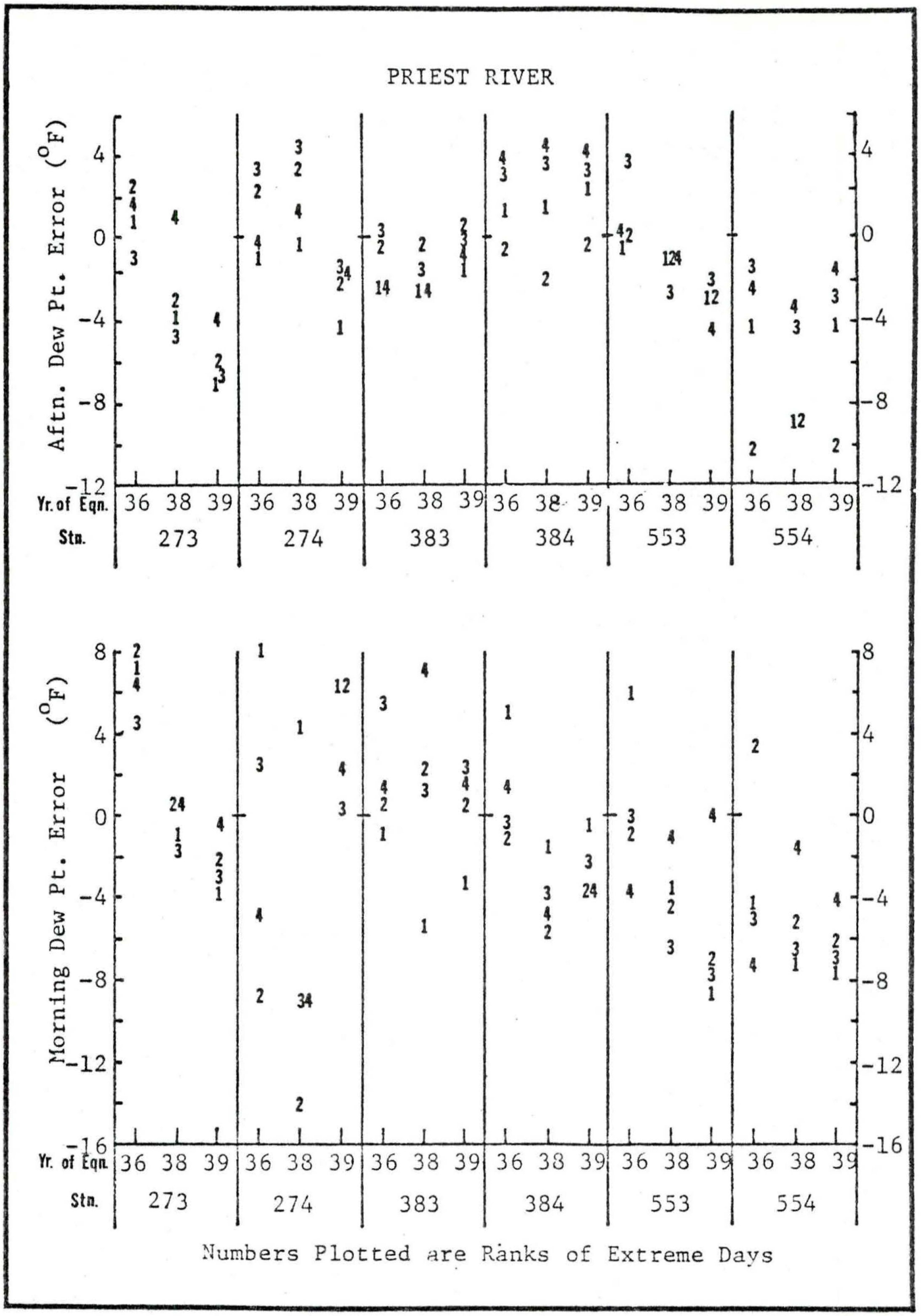

Figure C-2d,e. Priest River Extreme Day Accuracy: (d) Afternoon Dew Point; (e) Morning Dew Point.

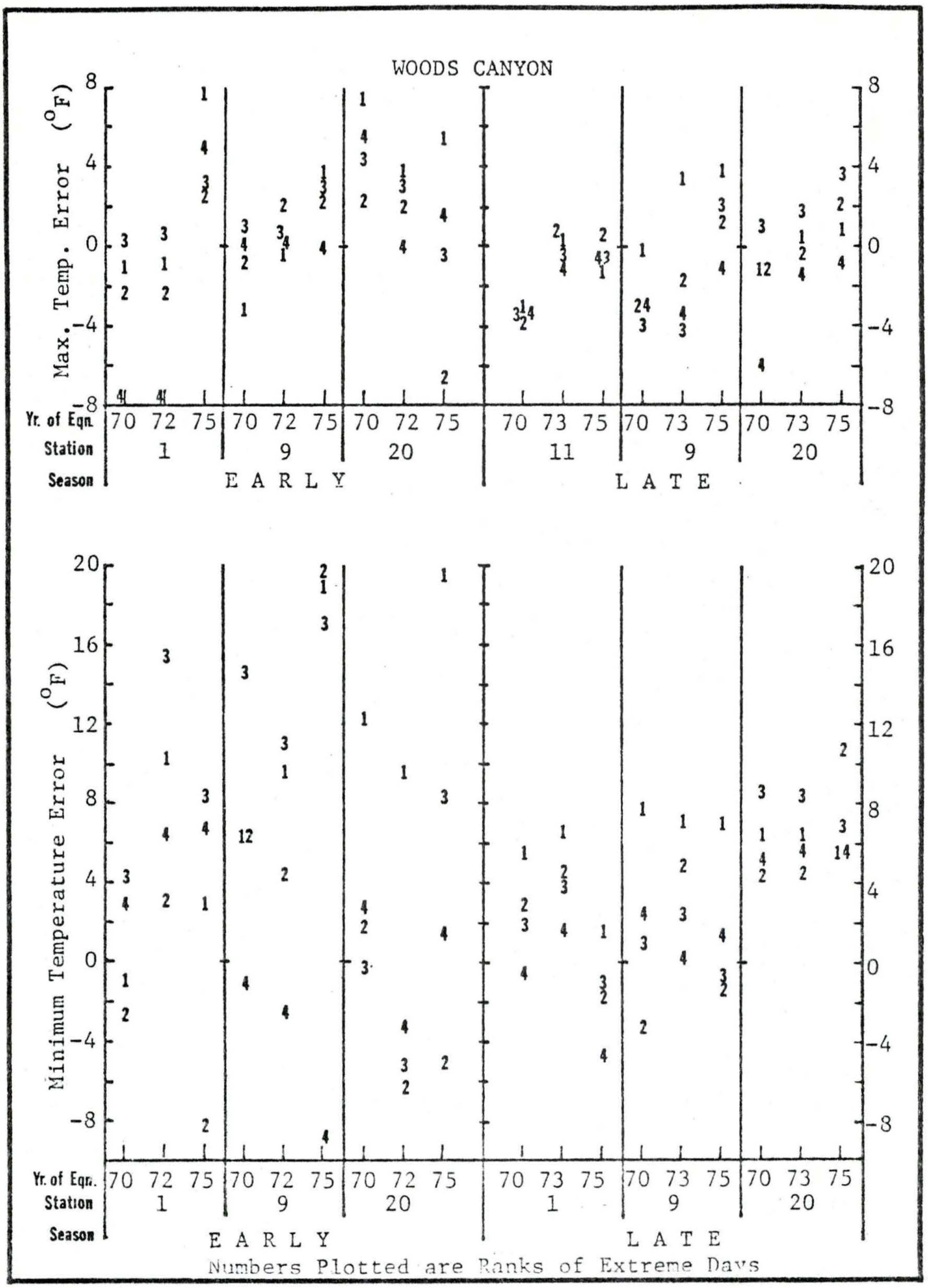

Figure C-2a,b. Woods Canyon Extreme Day Accuracy: (a) Maximum Temperature; (b) Minimum Temperature.

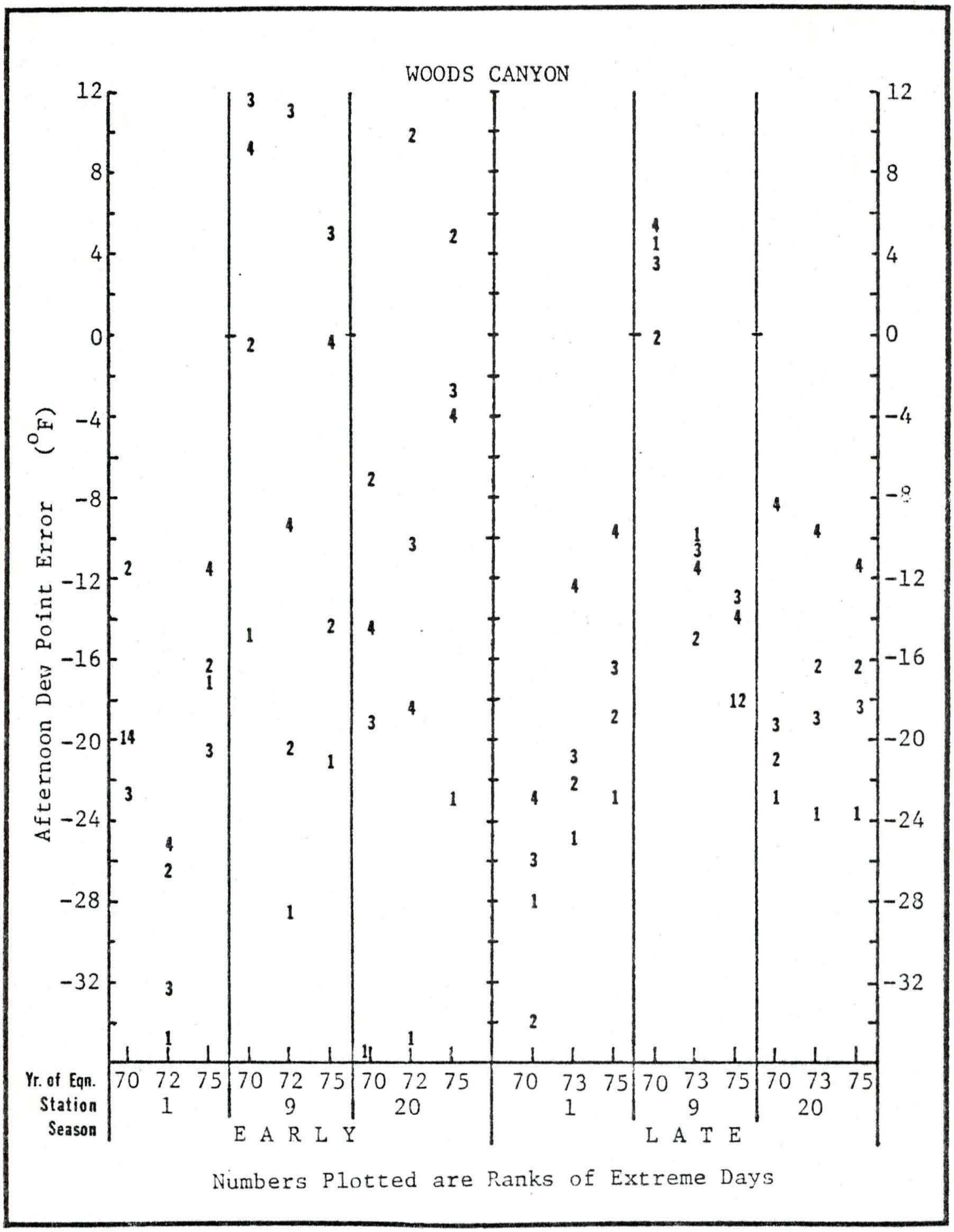

Figure C-2c. Woods Canyon Extreme Day Accuracy: Afternoon Dew Point.

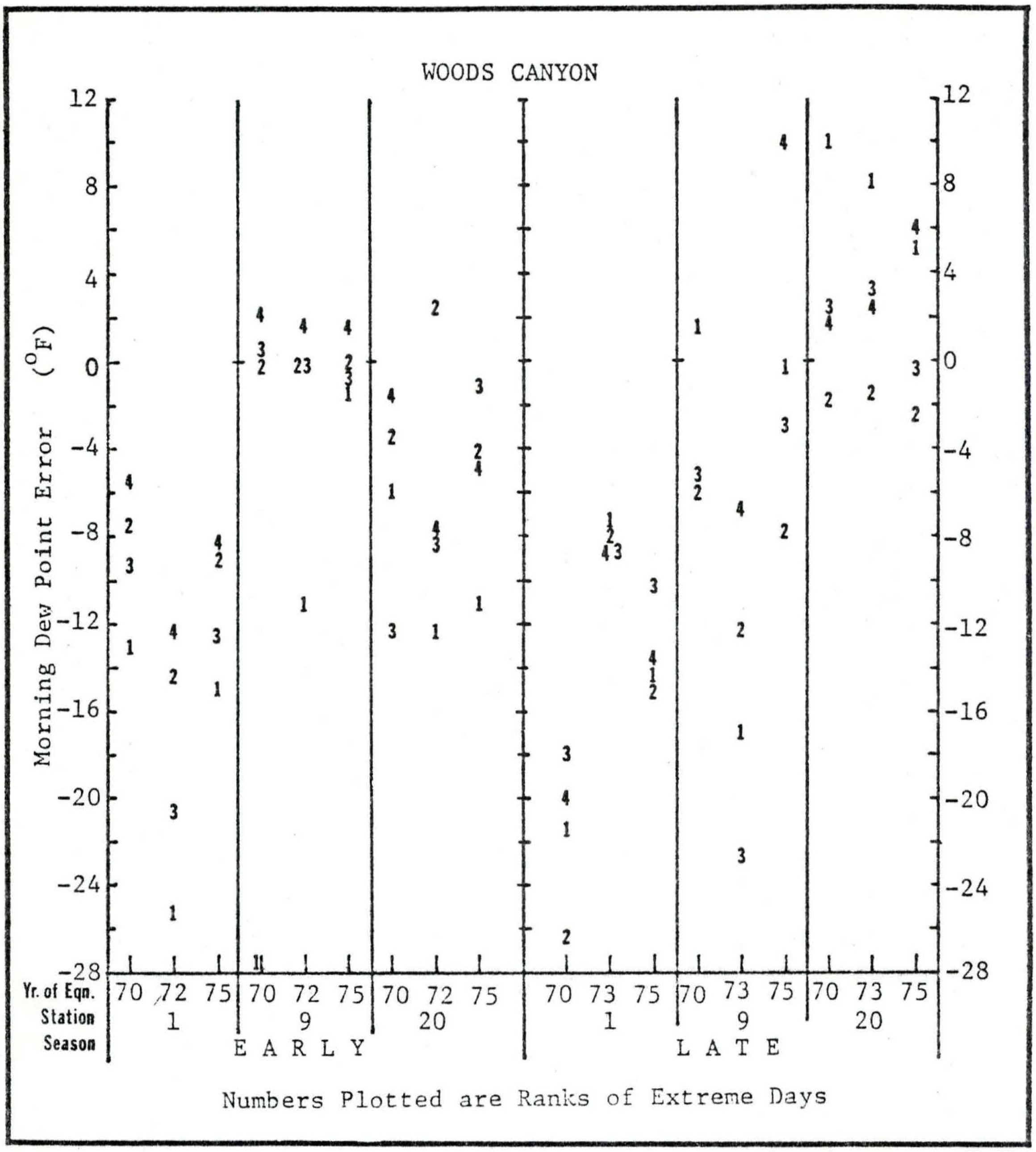

Figure C-2d. Woods Canyon Extreme Day Accuracy: Morning Dew Point.